Actuation and Response in Microsystems

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THz and nm Transistors for 1-1000 GHz Electronics

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The End (of Moore's Law) is Near (?)

It's a great time to be working on electronics !

Things to work on:

InP transistors: extend to 3-4 THz→GHz & low-THz ICs

GaN HEMTs: powerful transmitters from 1-300 GHz

Si MOSFETs: scale them past 16 nm

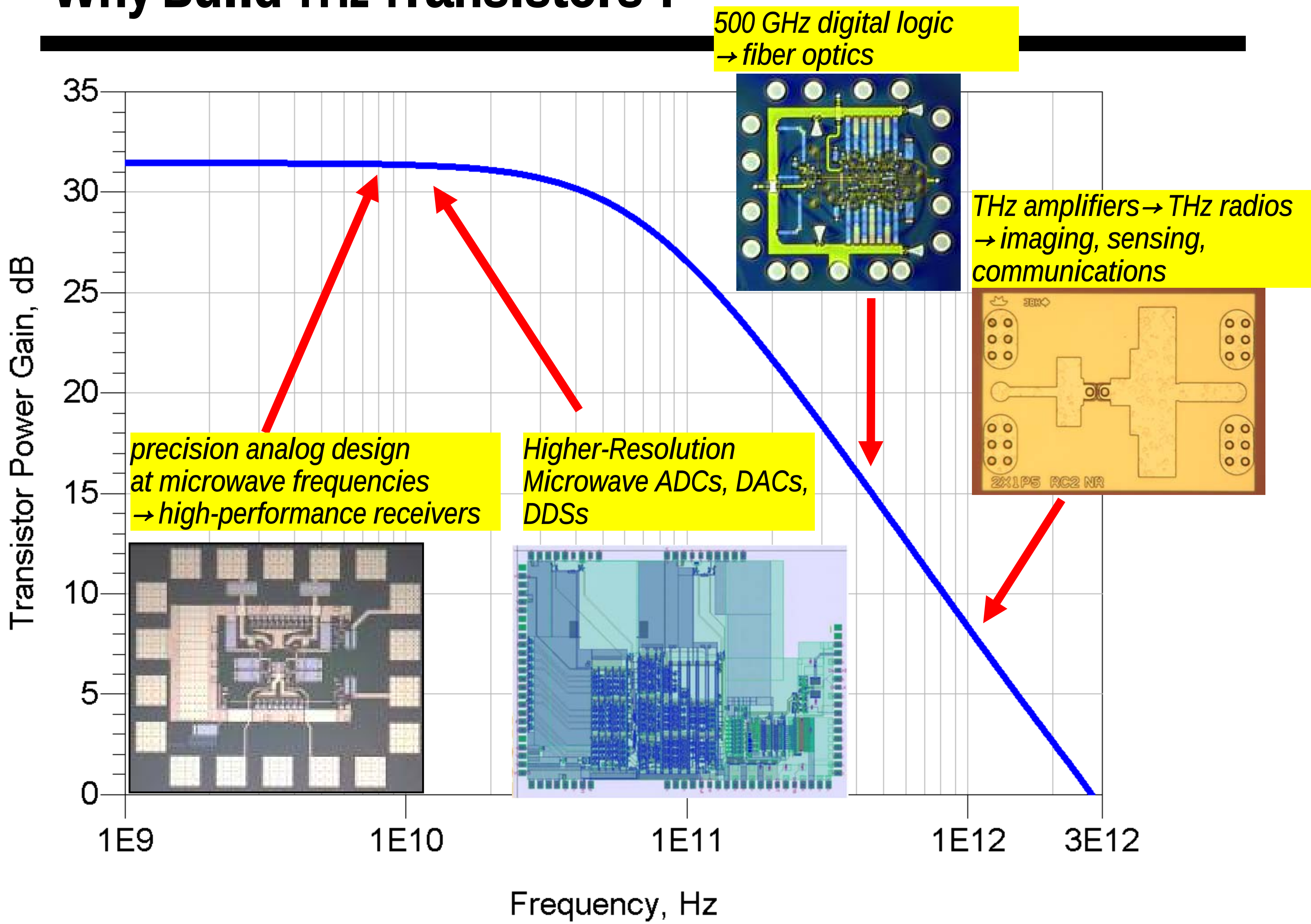
III-V MOSFETs: help keep VLSI scaling (maybe)

VLSI transistors: subvert Boltzmann→solve power crisis

mm-wave VLSI: massively complex ICs to re-invent radio

Why
THZ Transistors ?

Why Build THz Transistors ?



How to Make THz Transistors

Frequency Limits and Scaling Laws of (most) Electron Devices

$$\tau \propto \text{thickness}$$

$$C \propto \text{area} / \text{thickness}$$

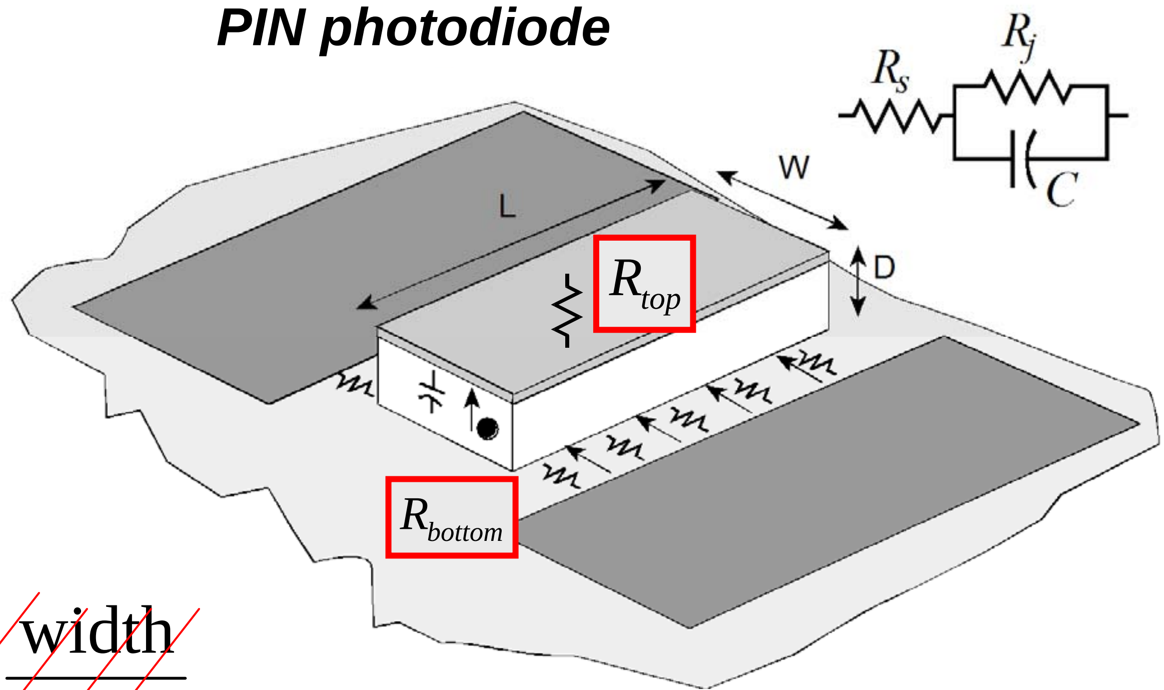
$$R_{top} \propto \rho_{contact} / \text{area}$$

$$R_{bottom} \propto \frac{\rho_{contact}}{\text{area}} + \frac{\rho_{sheet}}{4} \cdot \frac{\text{width}}{\text{length}}$$

$$I_{\text{max, space-charge-limit}} \propto \text{area} / (\text{thickness})^2$$

$$\Delta T \propto \frac{\text{power}}{\text{length}} \times \log\left(\frac{\text{length}}{\text{width}}\right)$$

PIN photodiode



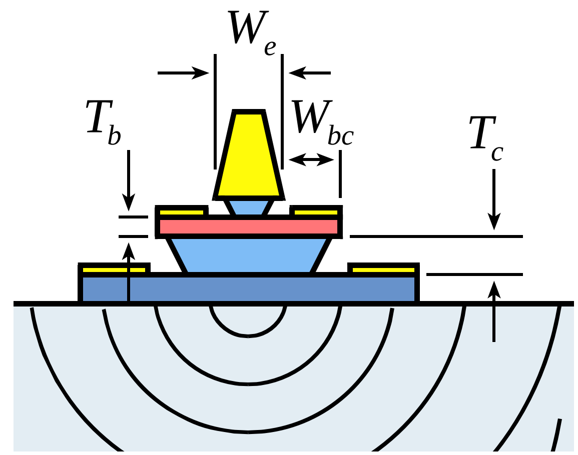
To double bandwidth,

reduce thicknesses 2:1 Improve contacts 4:1

reduce width 4:1, keep constant length

increase current density 4:1

Bipolar Transistor Scaling Laws



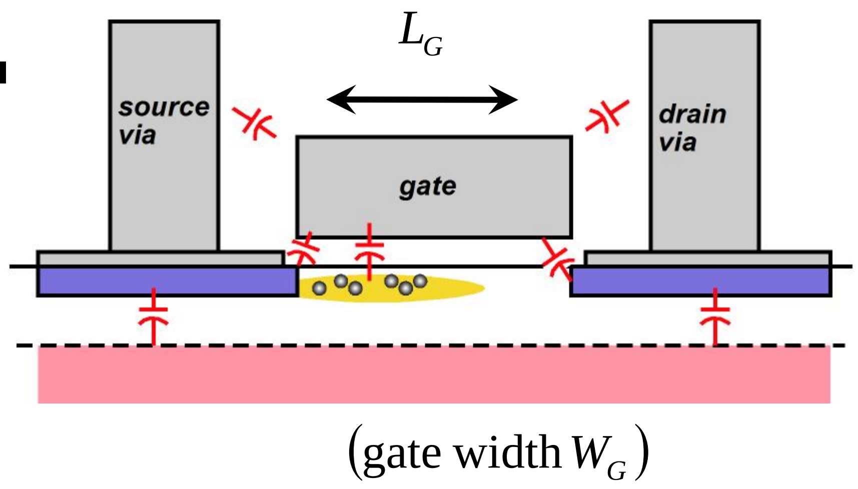
Changes required to double transistor bandwidth:

(emitter length L_E)

parameter	change
collector depletion layer thickness	decrease 2:1
base thickness	decrease 1.414:1
emitter junction width	decrease 4:1
collector junction width	decrease 4:1
emitter contact resistance	decrease 4:1
current density	increase 4:1
base contact resistivity	decrease 4:1

Linewidths scale as the inverse square of bandwidth because thermal constraints dominate.

FET Scaling Laws



Changes required to double transistor bandwidth:

parameter	change
gate length	decrease 2:1
gate dielectric capacitance density	increase 2:1
gate dielectric equivalent thickness	decrease 2:1
channel electron density	increase 2:1
source & drain contact resistance	decrease 4:1
current density (mA/μm)	increase 2:1

Linewidths scale as the inverse of bandwidth because fringing capacitance does not scale.

THz & nm Transistors: it's all about the interfaces

Metal-semiconductor interfaces (Ohmic contacts):
<u>very low resistivity</u>

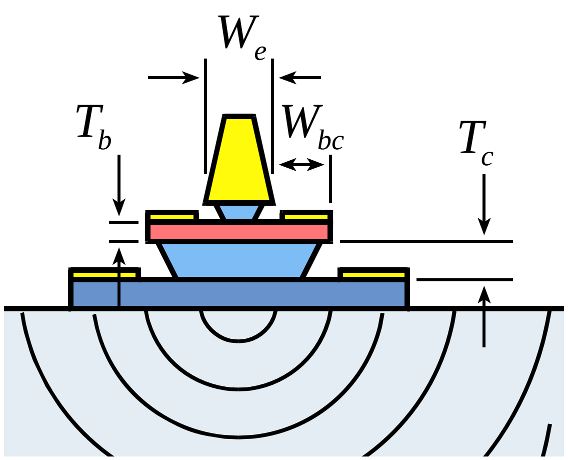
Dielectric-semiconductor interfaces (Gate dielectrics):
<u>very high capacitance density</u>

Transistor & IC thermal resistivity.

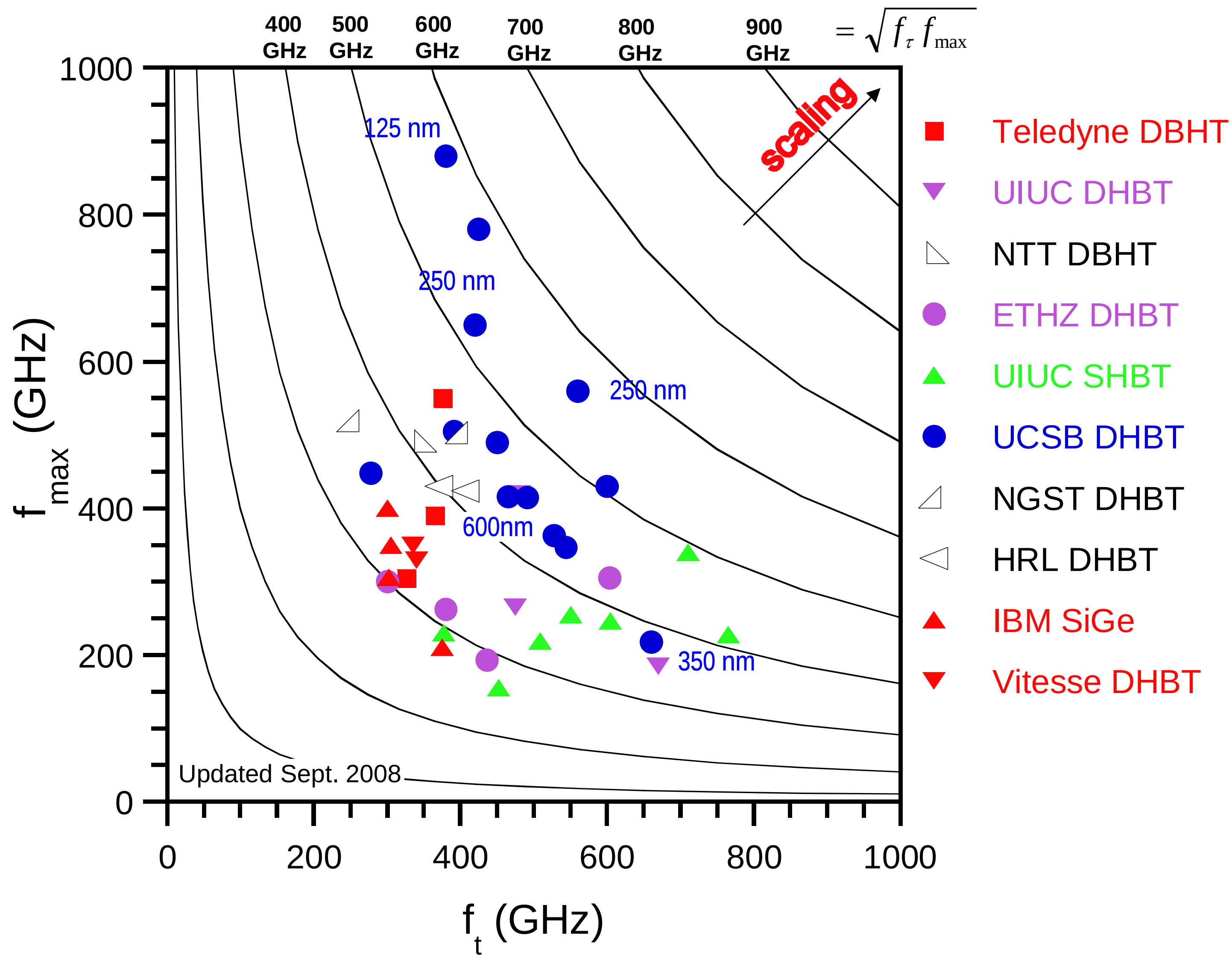
THz
Bipolar Transistors

InP Bipolar Transistor Scaling Roadmap

	industry	university →industry	university 2007-9	appears feasible	maybe
emitter	512	256	128	64	32 nm width
	16	8	4	2	1 Ω·μm² access ρ
base	300	175	120	60	30 nm contact width,
	20	10	5	2.5	1.25 Ω·μm² contact ρ
collector	150	106	75	53	37.5 nm thick,
	4.5	9	18	36	72 mA/μm² current density
	4.9	4	3.3	2.75	2-2.5 V, breakdown
f_τ	370	520	730	1000	1400 GHz
f_{max}	490	850	1300	2000	2800 GHz
power amplifiers	245	430	660	1000	1400 GHz
digital 2:1 divider	150	240	330	480	660 GHz



InP DHBTs: September 2008



popular metrics :

f_τ or f_{max} alone

$(f_\tau + f_{max})/2$

$\sqrt{f_\tau f_{max}}$

$(1/f_\tau + 1/f_{max})^{-1}$

much better metrics :

power amplifiers:

PAE, associated gain,

mW/μm

low noise amplifiers:

F_{min}, associated gain,

digital:

f_{clock}, hence

$(C_{cb}\Delta V / I_c)$,

$(R_{ex} I_c / \Delta V)$,

$(R_{bb} I_c / \Delta V)$,

$(\tau_b + \tau_c)$

Ohmic Contacts Good Enough for 3 THz Transistors

64 nm (2.0 THz) HBT needs ~ 2 Ω - μm^2 contact resistivities

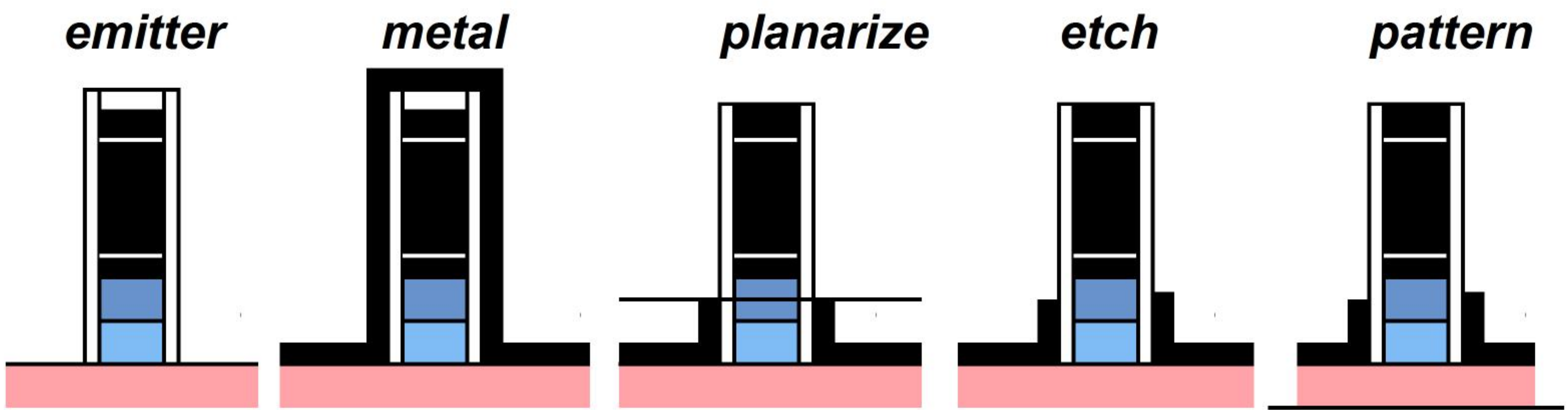
32 nm (2.8 THz) HBT needs ~ 1 Ω - μm^2

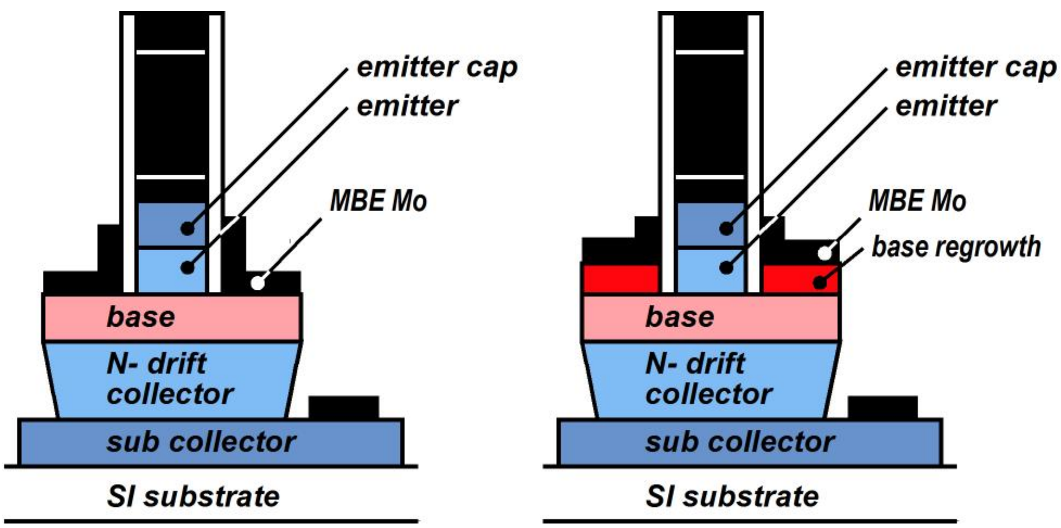
Contacts to N-InGaAs:*		
Mo	*MBE in-situ*	*0.3 (+/- 0.3) Ω - μm^2*
TiW	*ex-situ*	*~1 to 2 Ω - μm^2*

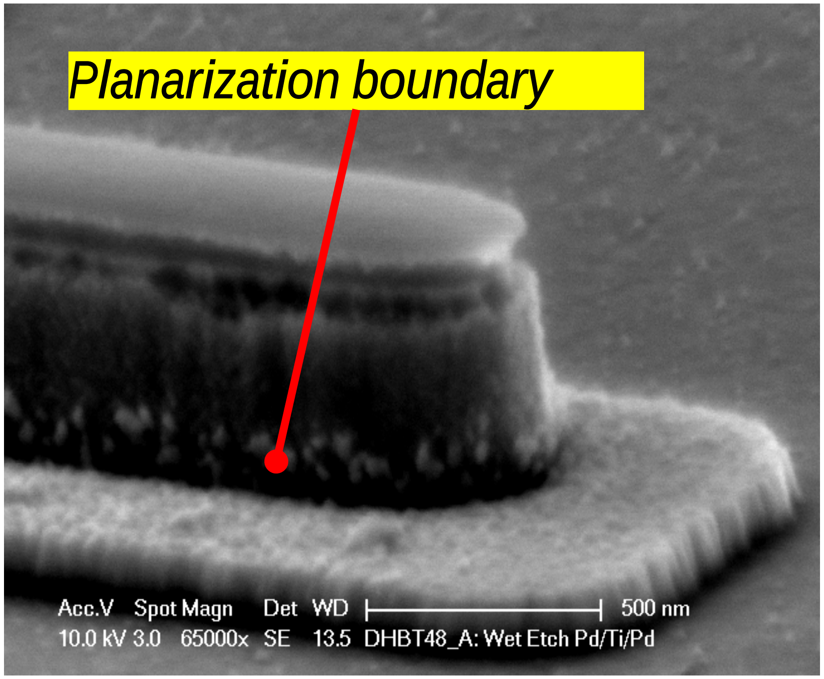
Contacts to P-InGaAs:		
Mo	*MBE in-situ*	*below 2.5 Ω - μm^2*
Pd/...	*ex-situ*	*0.36 (+/- 0.3) Ω - μm^2*

**measured emitter resistance remains higher than that of contacts.*

THz HBTs: MOSFET-like Processes for 64, 32 nm Nodes

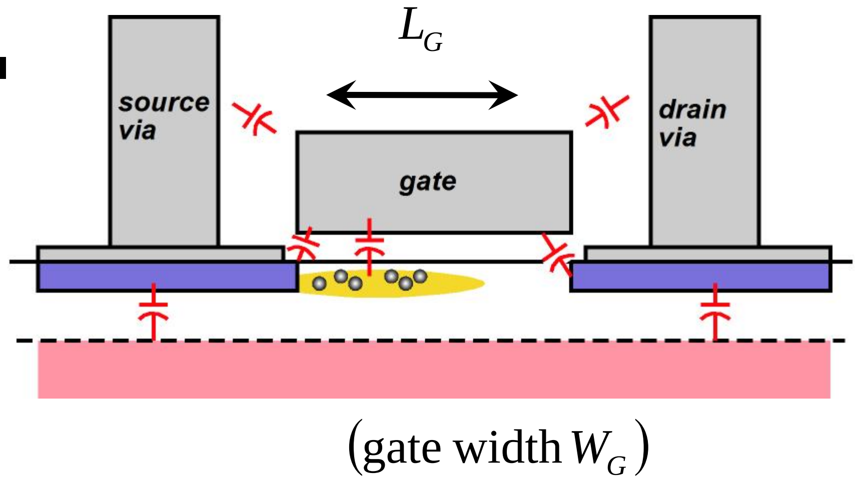






nm MOSFETs

FET Scaling Laws



Changes required to double transistor bandwidth:

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gate dielectric capacitance density	increase 2:1
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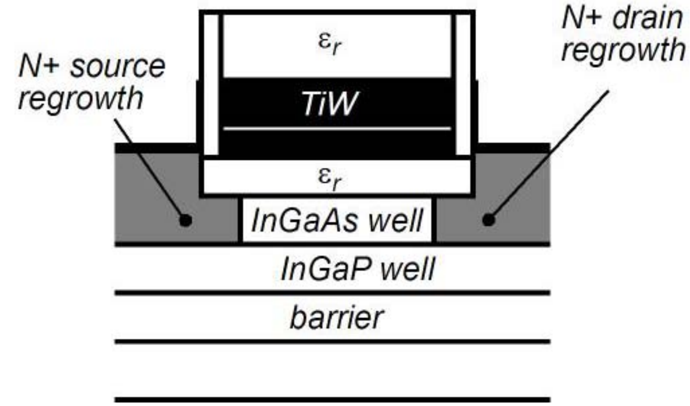
channel electron density	increase 2:1
source & drain contact resistance	decrease 4:1
current density (mA/μm)	increase 2:1

What do we do if gate dielectric cannot be further scaled ?

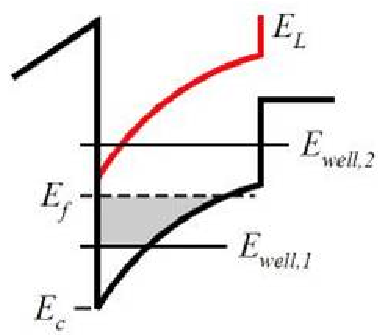
III-V MOSFETs for VLSI

<u>What is it ?</u>
MOSFET with an InGaAs channel



<u>Why do it ?</u>
low electron effective mass→higher electron velocity
more current, less charge at a given insulator thickness & gate length
very low access resistance

<u>What are the problems ?</u>
low electron effective mass→constraints on scaling !
must grow high-K on InGaAs, must grow InGaAs on Si

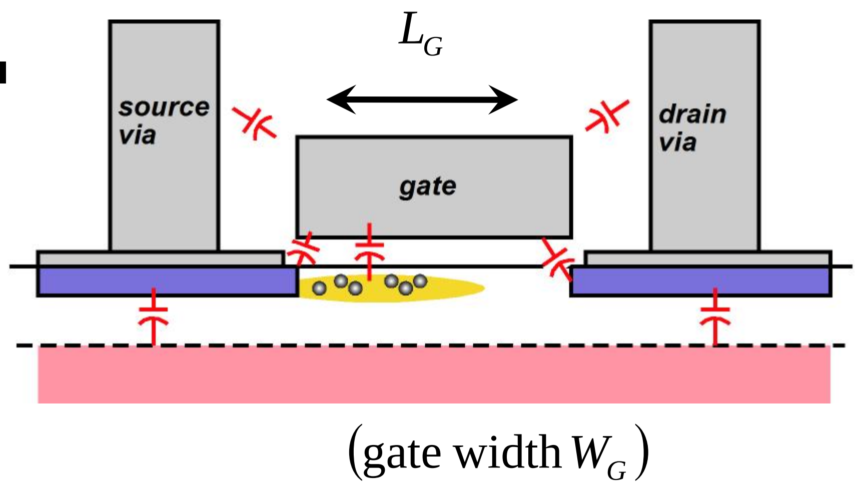


<u>Synopsis</u>
III-V MOSFET might win... <u>if</u> Si gate dielectric cannot scale below 0.5 nm

THZ Field-Effect Transistors

(THz HEMTs)

FET Scaling Laws



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current density (mA/μm)	increase 2:1

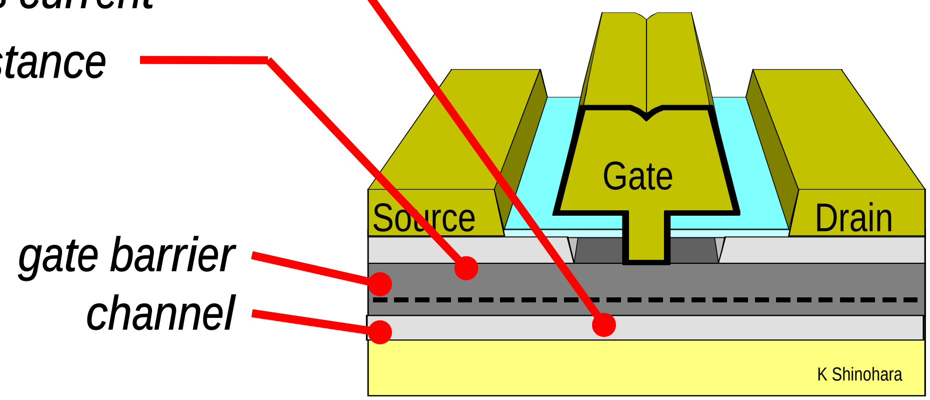
InGaAs HEMTs are best for mm-wave low-noise receivers...
...but there are difficulties in improving them further.

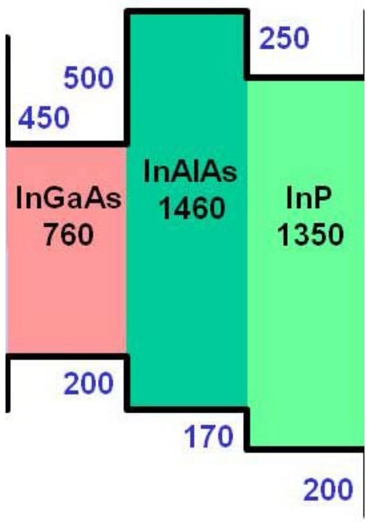
Why HEMTs are Hard to Improve

1st challenge with HEMTs: reducing access resistance

low electron density under gate recess → limits current

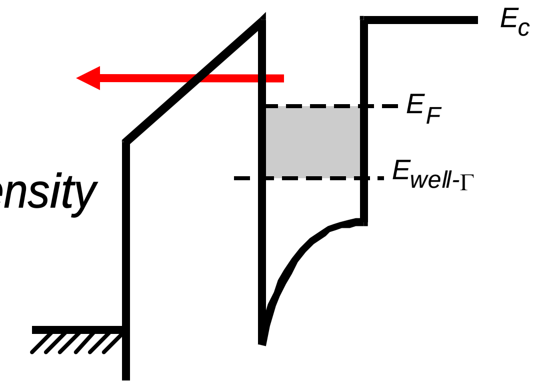
gate barrier lies under S/D contacts → resistance





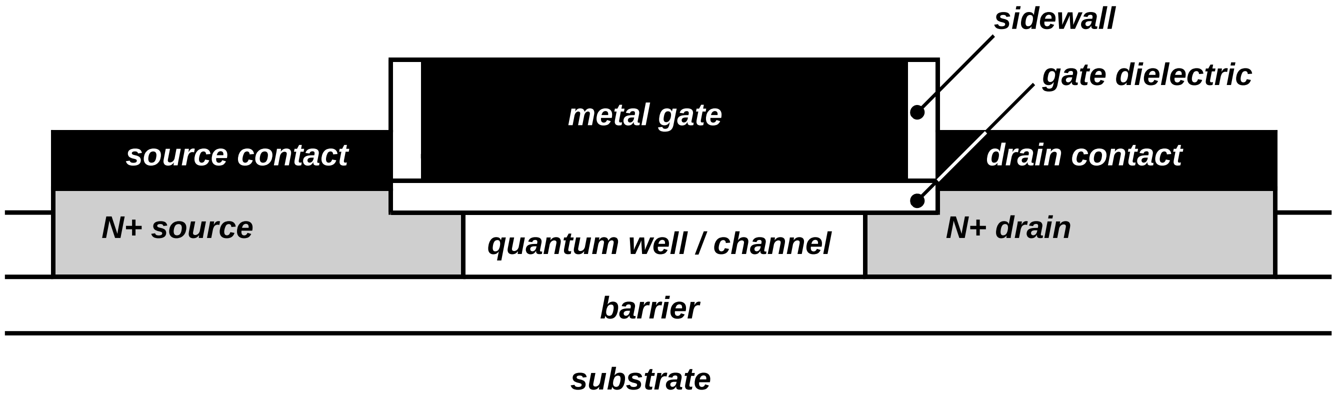
2nd challenge with HEMTs: low gate barrier

high tunneling currents with thin barrier
high emission currents with high electron density



III-V MOSFETs do not face these scaling challenges

InGaAs MOSFETs as THz Low-Noise Amplifiers



Why ?

Much lower access resistance in S/D regions

Higher gate barrier→ higher feasible electron density in channel

Higher gate barrier→ gate dielectric can be made thinner

Estimated Performance (?)

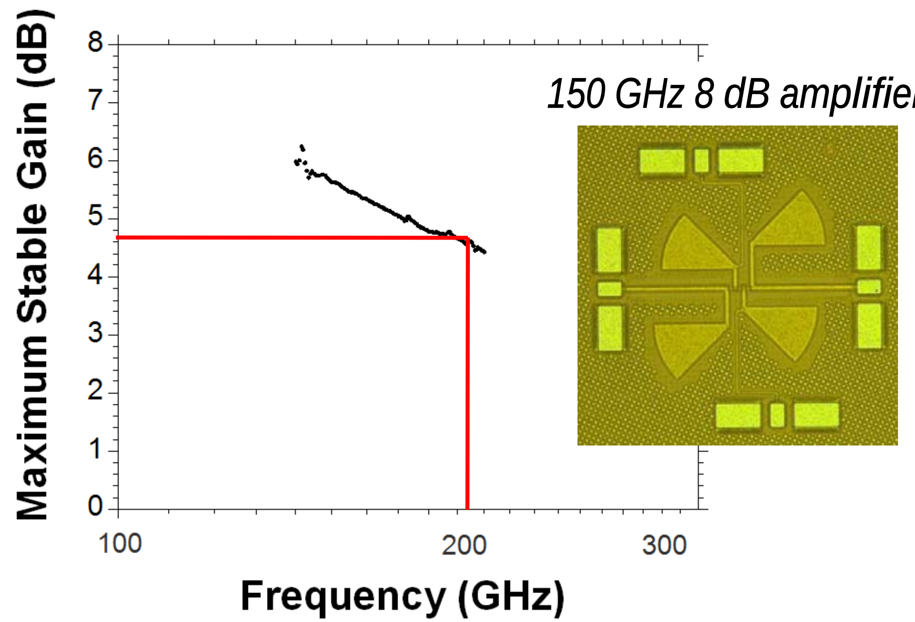
2 THz cutoff frequencies at 32 nm gate length

VSLI for mm-wave & sub-mm-wave systems

Billions of 700-GHz Transistors→ Imaging & Arrays

65 nm CMOS: ~5 dB gain @ 200 GHz

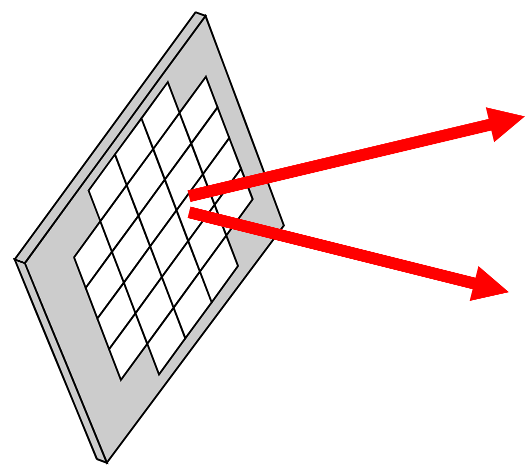
22 nm will be much faster yet.



What can you do with a few billion 700-GHz transistors ?

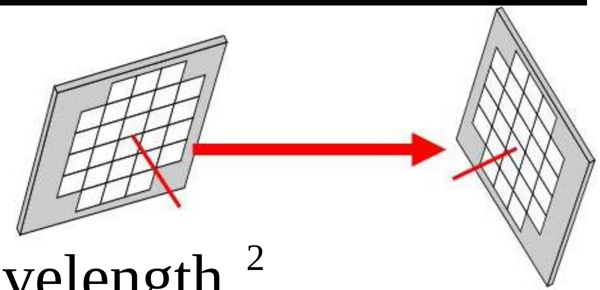
Build Transmitter / Receiver Arrays

100's or 1000's of transmitters or receivers
...on < 1 cm^2 IC area
...operating at 100-500 GHz.



Billions of 700-GHz Transistors→ Imaging & Arrays

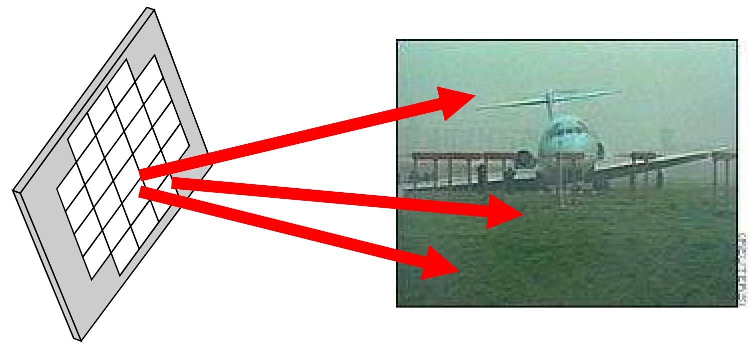
Arrays for point-point radio links:



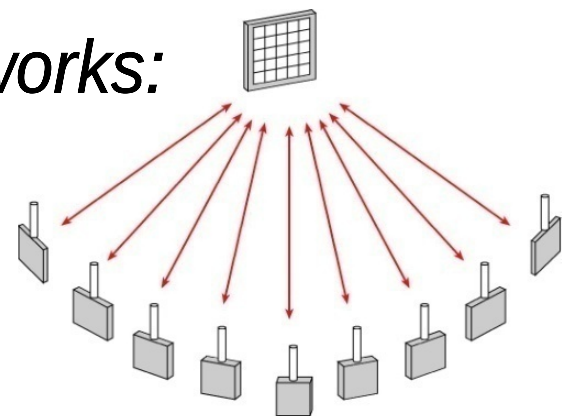
$$\text{bit rate} \cdot \text{distance}^2 \propto (\#\ \text{array elements})^2 \cdot \text{wavelength}^2$$

Arrays for (sub)-mm-wave imaging :

$$\#\ \text{resovable pixels} = \#\ \text{array elements}$$



Arrays for Spatial-Division-Multiplexing Networks:



$$\#\ \text{independen t beams} = \#\ \text{array elements}$$

$$\leq \frac{4 \cdot \text{array area}}{\text{wavelength}^2}$$

It's a great time to be working on electronics !

Device scaling (Moore's Law) is not yet over.

Challenges in scaling:
contacts, dielectrics, heat

Multi-THz transistors:
for systems at very high frequencies
for better performance at moderate frequencies

Vast #s of THz transistors
complex systems
new applications.... imaging, radio, and more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