High-Frequency Transistors High-Frequency ICs

Technologies & Applications

Mark Rodwell
University of California, Santa Barbara

rodwell@ece.ucsb.edu   805-893-3244, 805-893-2362 fax

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **06 MAR 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High-Frequency Transistors High-Frequency ICs Technologies & Applications**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, Santa Barbara**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
DARPA Microsystems Technology Symposium held in San Jose, California on March 5-7, 2007. Presentations, The original document contains color images.

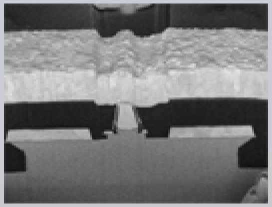
14. ABSTRACT

15. SUBJECT TERMS

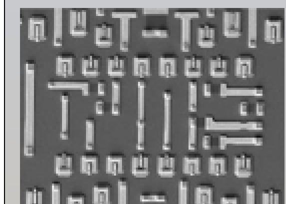
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**21**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

UCSB High-Frequency Electronics Group

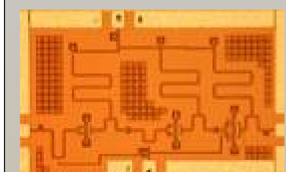


Ultra High-Frequency III-V Transistors:
Aim for 1-2 THz cutoff frequencies
InGaAs/InP bipolar transistors
InGaAs/InP field-effect transistors
.

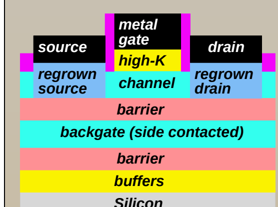


Ultra High Frequency III-V ICs
Aim for 500+ GHz digital clock rates
Aim for 700+ GHz amplifiers
other advanced circuits

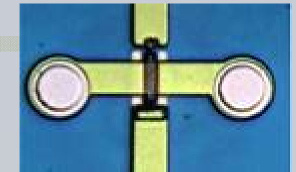
DARPA
ONR
SRC
NSF

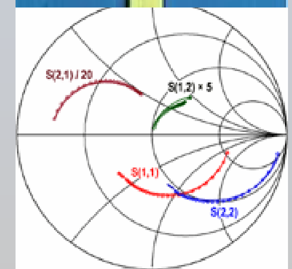


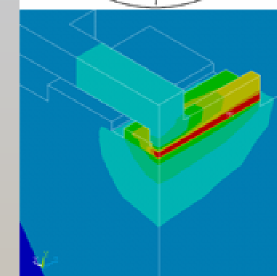
mm-wave ICs in Silicon (60-90 GHz)
10-160 Gb/s wireless,
mm-wave sensor networks
monolithic arrays for radar & communications
mm--wave MIMO

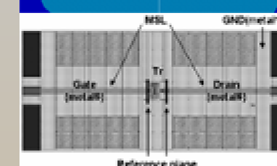


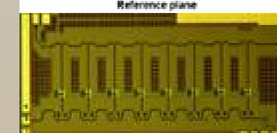
III-V CMOS for Si VLSI
III-V channel MOSFETs for sub-22-nm scaling

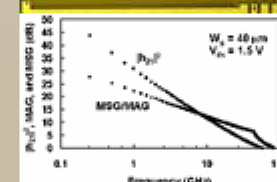


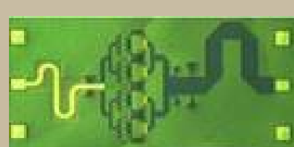


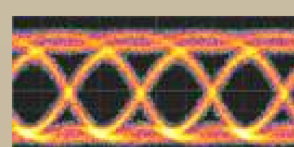


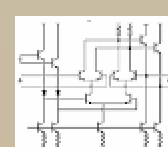


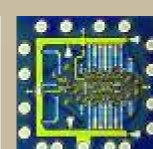


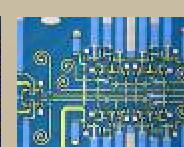








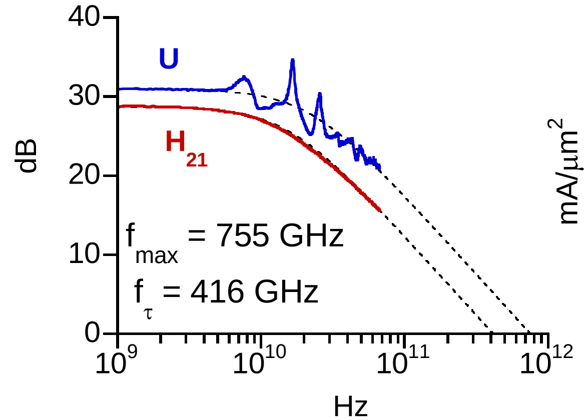


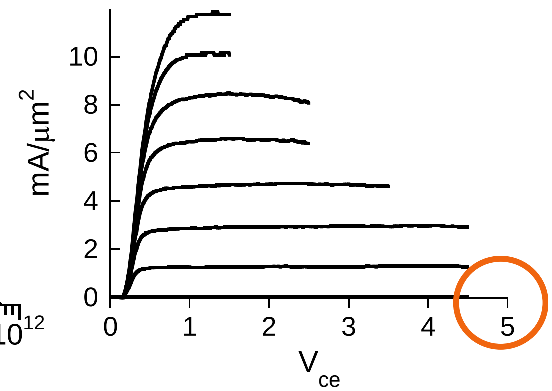


THz Transistors are coming soon

InP Bipolars: 250 nm generation: → 750 GHz f_{max}, 400 GHz f_τ, 5 V BV_{CEO}

125 nm & 62 nm nodes
→ ~THz devices

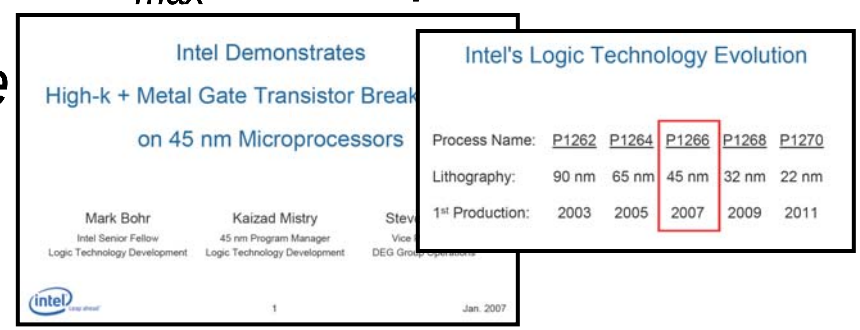




IBM IEDM '06: 65 nm SOI CMOS → 450 GHz f_{max}, ~1 V operation

Intel Jan '07: 45 nm / high-K / metal gate

→ continued rapid progress



What applications for III-V bipolars ?

What applications for mm-wave CMOS ?

So our focus....

InP Bipolar Transistors

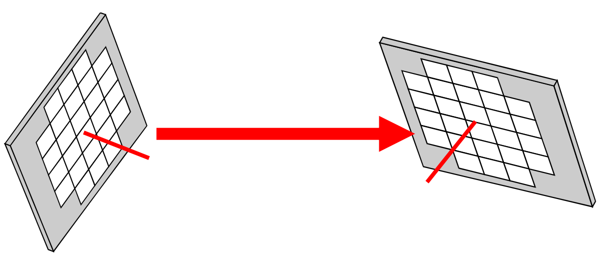
what performance can we achieve ?

what are the applications ?

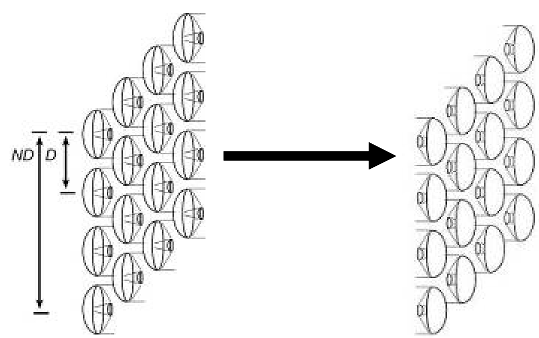
65 / 45 / 33 ... nm CMOS

vast #s of near-THz transistors

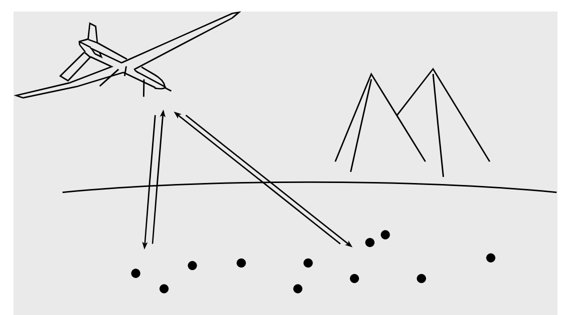
what NEW mm-wave applications will this enable ?



massive monolithic mm-wave arrays
→ 1 Gb/s over ~1 km



mm-wave MIMO



mm-wave imaging
sensor networks

Let's look at InP and CMOS prospects & applications...

InP Bipolar Transistors

InP Bipolar Transistors---what are they for ?

Compared to SiGe:
~3:1 larger bandwidth at a given feature size
~3:1 larger voltage at a given bandwidth

Compared to CMOS
higher bandwidth at 10x the feature size
much higher breakdown voltage
analog precision

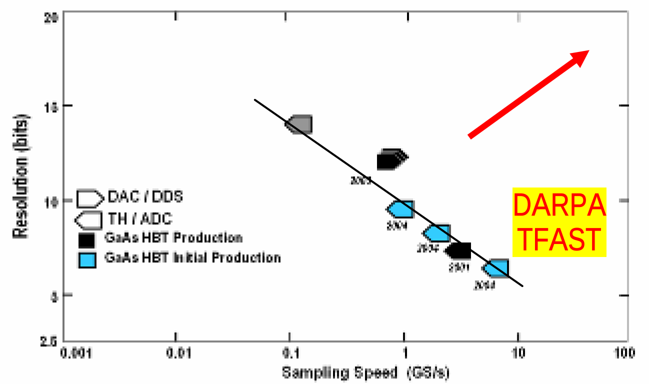
InP HBT:
~ $10,000 mask cost, ~2-3 month fab cycles

speed *voltage* *low volume*

Applications of THz Transistors

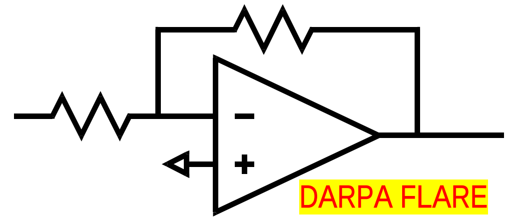
microwave ADCs and DACs

more resolution & more bandwidth

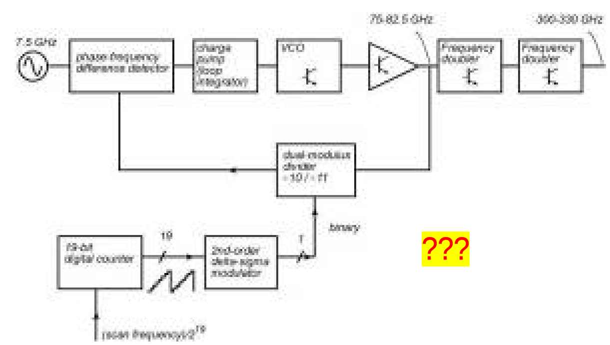


microwave op-amps

high IP3 at low DC power at 2-10 GHz

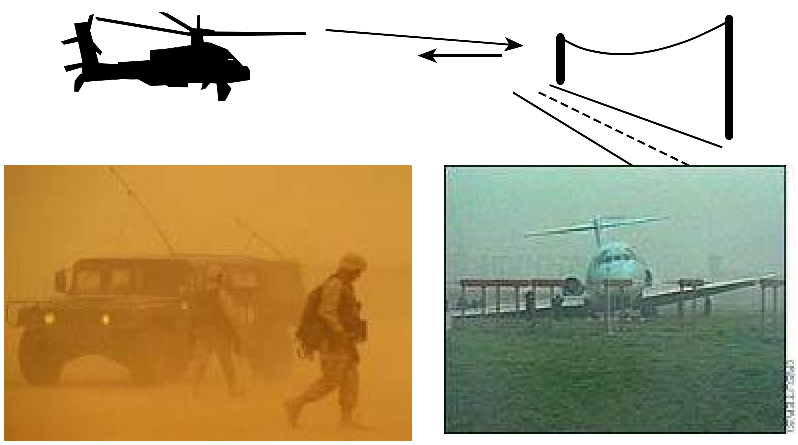


single-chip 300-400 GHz spectrometers (gas detection)



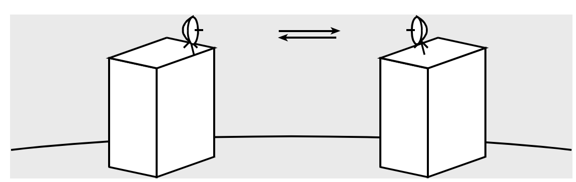
???

340 GHz or 650 GHz imaging systems

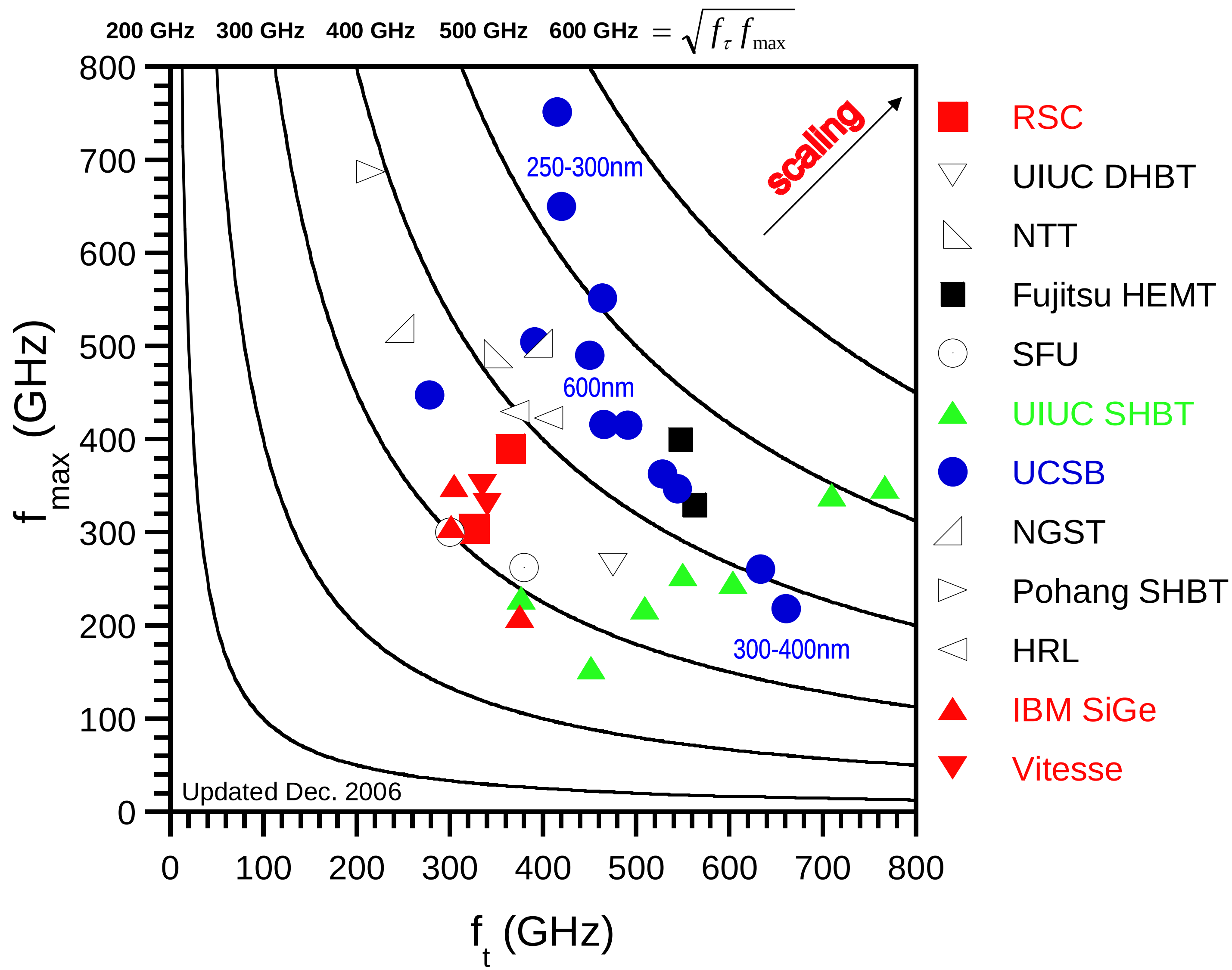


DARPA SWIFT

sub-mm-wave communications



Present Status: Fast Bipolar Transistors



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 :

<u>power amplifiers</u>:

PAE, associated gain, mW/μm

<u>low noise amplifiers</u>:

F_{min}, associated gain,

<u>digital</u>:

f_{clock}, hence

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

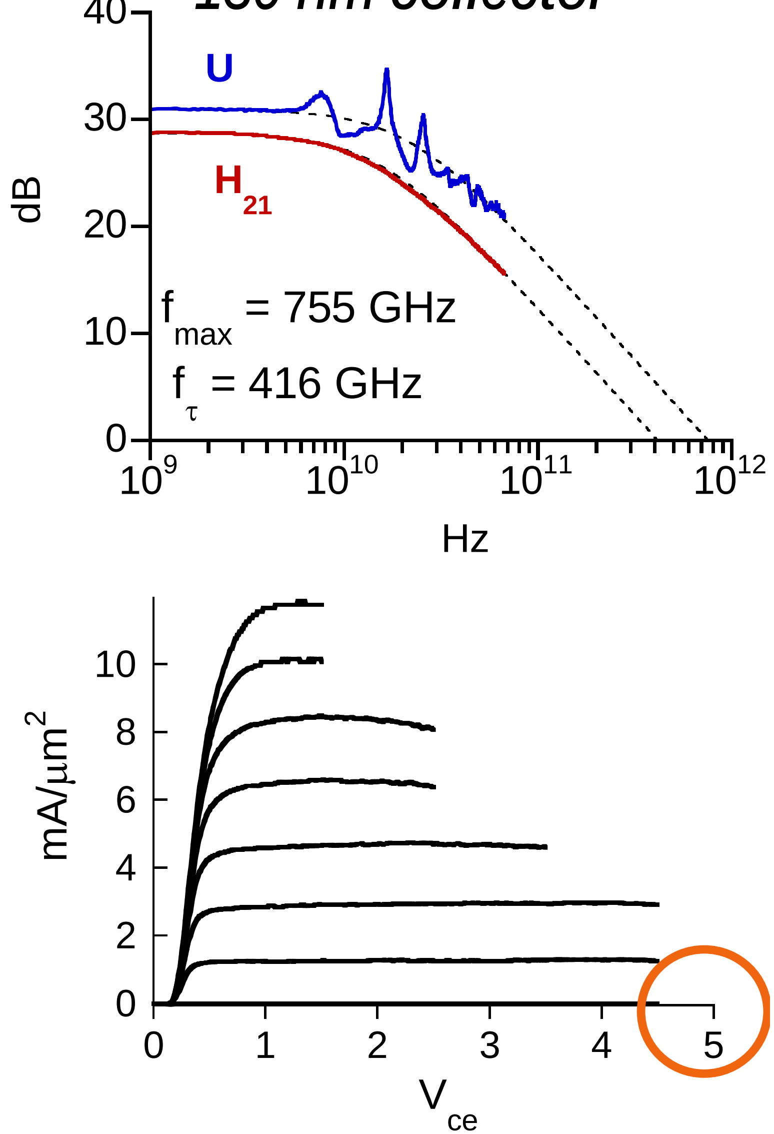
$(R_{ex} I_c / \Delta V)$,

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

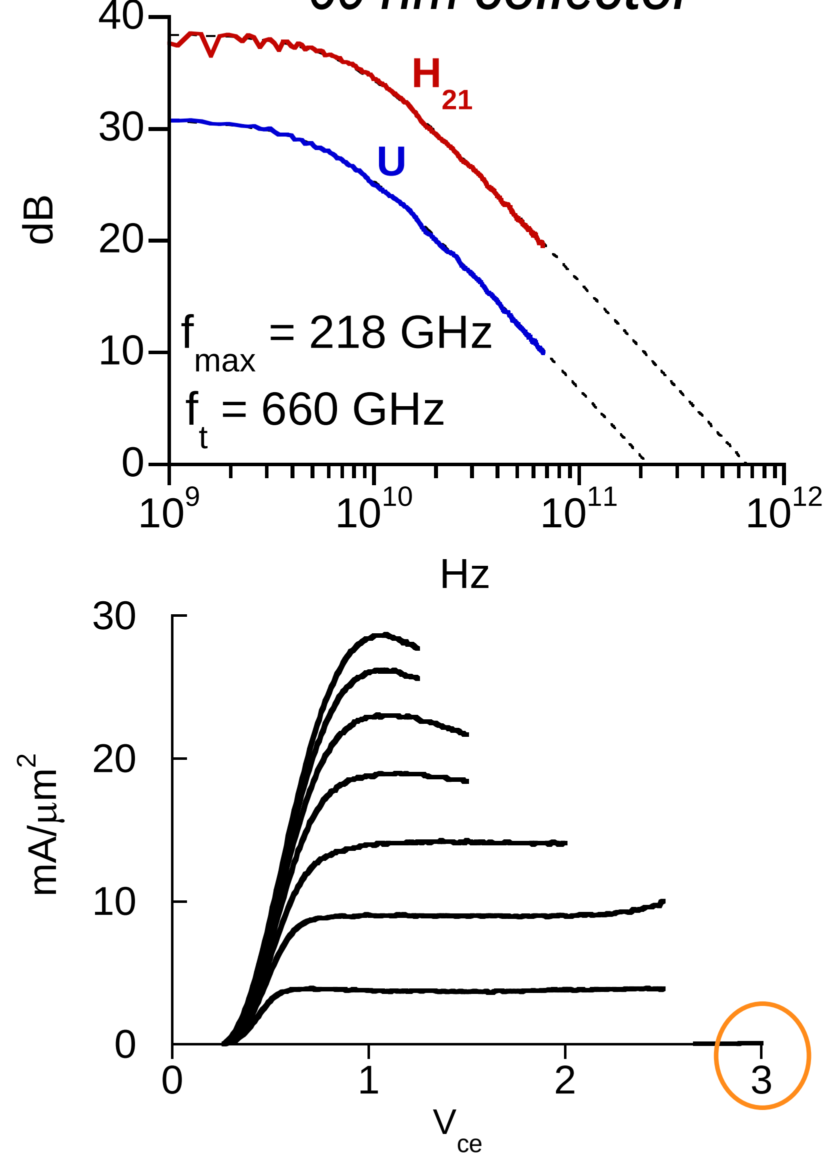
$(\tau_b + \tau_c)$

UCSB DHBTs: 250 nm Scaling Generation

150 nm collector

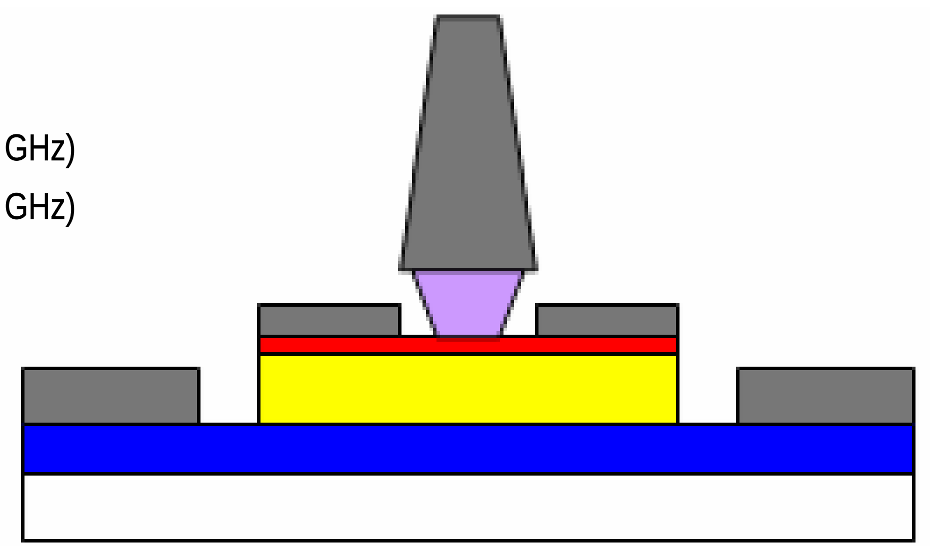


60 nm collector



2005: InP DHBTs @ 500 nm Scaling Generation

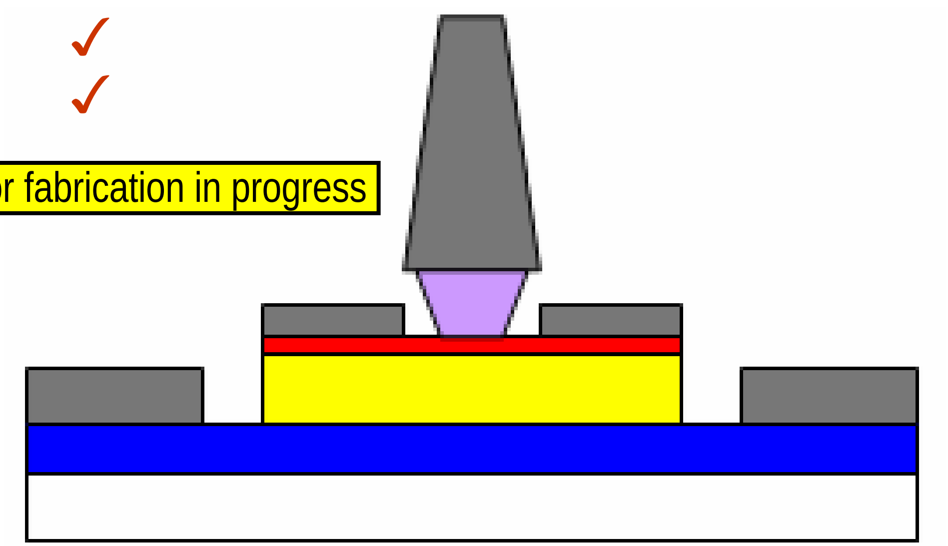
emitter	500 nm width	✓	
	16 $\Omega\cdot\mu m^2$ contact ρ	✓	
base	300 width,	✓	
	20 $\Omega\cdot\mu m^2$ contact ρ	✓	
collector	150 nm thick,	✓	
	5 $mA/\mu m^2$ current density	✓	
	5 V, breakdown	✓	
f_τ	400 GHz	✓	
f_{max}	500 GHz	✓	
power amplifiers	250 GHz	✓	(178 GHz)
digital clock rate (static dividers)	160 GHz	✓	(150 GHz)



2006: 250 nm Scaling Generation, 1.414:1 faster

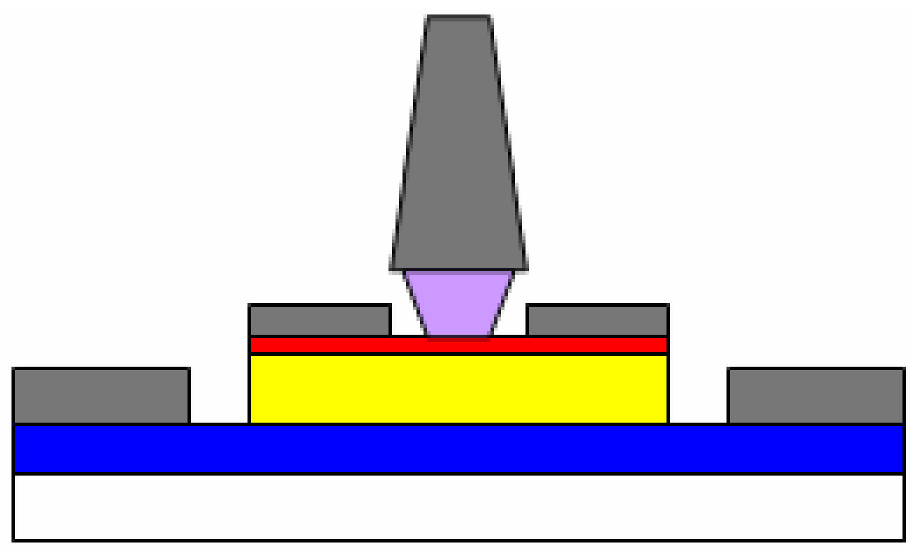
emitter	500	250 nm width		✓
	16	9 Ω·µm² access ρ		✓
base	300	150 width,		✓
	20	10 Ω·µm² contact ρ		✓
collector	150	100 nm thick,		✓
	5	10 mA/µm² current density		✓
	5	3.5 V, breakdown		✓
f_τ	400	500 GHz	(416 GHz)	✓
f_{max}	500	700 GHz	(755 GHz)	✓
power amplifiers	250	350 GHz		
digital clock rate (static dividers)	160	230 GHz		

Designs and / or fabrication in progress



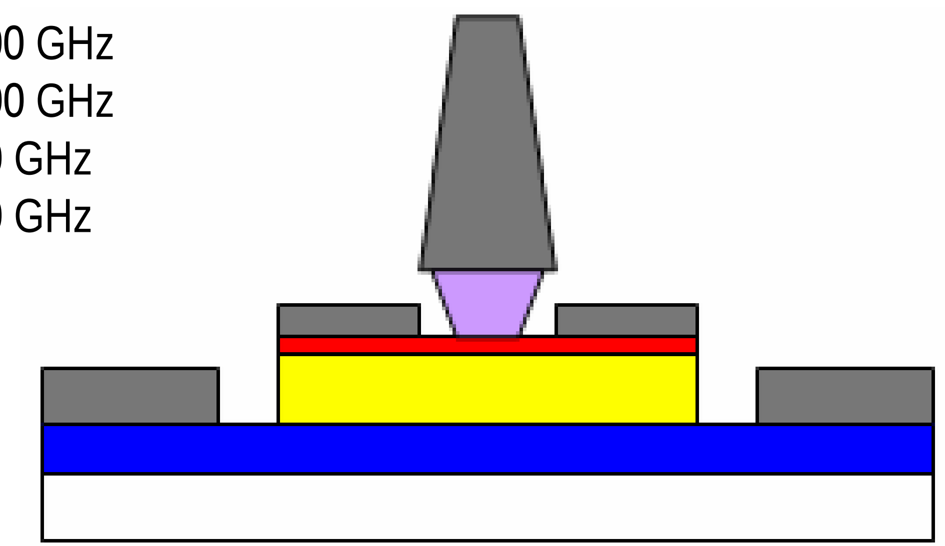
2007: 125 nm Scaling Generation → almost-THz HBT

emitter	500	250	125 nm width	✓
	16	9	4 $\Omega\cdot\mu m^2$ access ρ	✓
base	300	150	75 width,	✓
	20	10	5 $\Omega\cdot\mu m^2$ contact ρ	✓
collector	150	100	75 nm thick,	✓
	5	10	20 mA/μm^2 current density	✓
	5	3.5	3 V, breakdown	✓
f_τ	400	500	700 GHz	
f_{max}	500	700	1000 GHz	
power amplifiers	250	350	500 GHz	
digital clock rate (static dividers)	160	230	330 GHz	



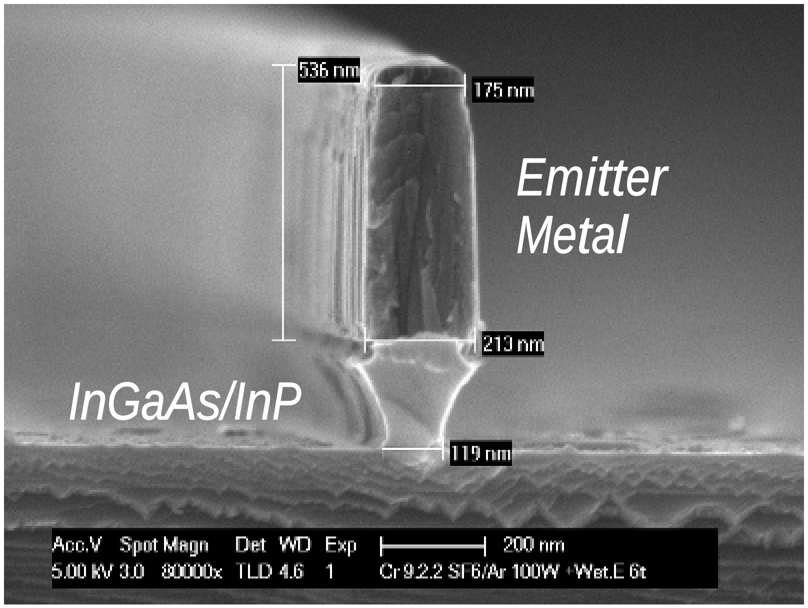
2008-9: 65 nm Scaling Generation→beyond 1-THz HBT

emitter	500	250	125	63 nm width
	16	9	4	2.5 Ω·μm² access ρ ✓
base	300	150	75	70 nm width,
	20	10	5	5 Ω·μm² contact ρ ✓
collector	150	100	75	53 nm thick,
	5	10	20	35 mA/μm² current density
	5	3.5	3	2.5 V, breakdown
f_τ	400	500	700	1000 GHz
f_{max}	500	700	1000	1500 GHz
power amplifiers	250	350	500	750 GHz
digital clock rate (static dividers)	160	230	330	450 GHz



Our first 125 nm DHBTs should come soon:

125 nm emitter process is ready



emitter contact resistivity ~ 0.7 Ω - μm^2

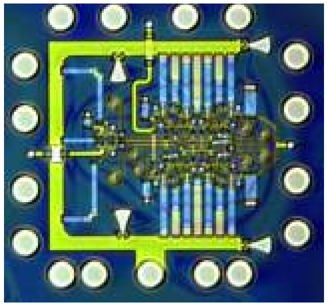
base contact resistivity ~ 3-5 Ω -μm^2

target performance ~ 700-900 GHz simultaneous f_t & f_{max}, 3-4 V breakdown

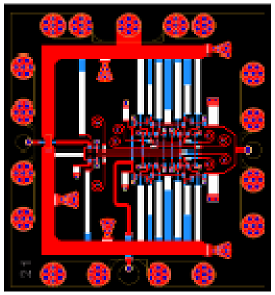
fabrication runs winter / spring 2007

IC designs: Past and Pending

150 GHz digital latches in 500 nm DHBT

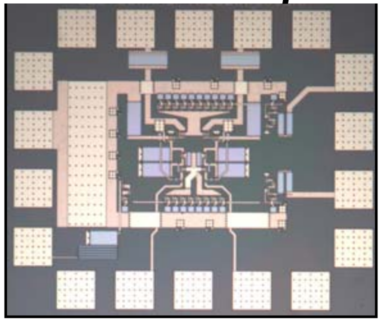


200 GHz latch designs in 250 nm DHBT



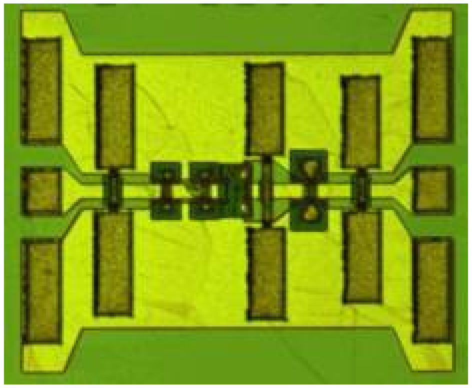
...fabrication on hold...

60 GHz gain-bandwidth op-amps

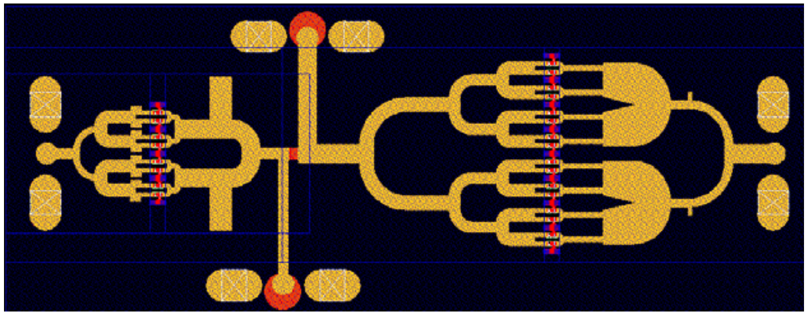


target: OIP3/P_{dc} >60:1

175 GHz amplifiers in 500 nm DHBT



340 GHz amplifier designs in 250 nm DHBT

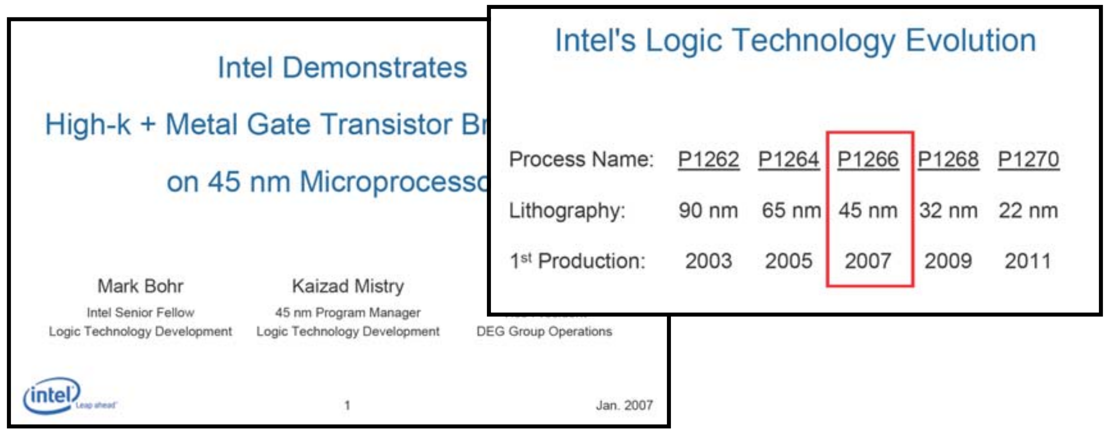


The proof of a fast transistor is a fast circuit

THz CMOS is coming soon

IBM IEDM '06: 65 nm SOI CMOS → 450 GHz f_{max}

Intel Jan '07: 45 nm / high-K / metal gate



Intel Demonstrates
High-k + Metal Gate Transistor Br
on 45 nm Microprocesso

Mark Bohr
Intel Senior Fellow
Logic Technology Development

Kaizad Mistry
45 nm Program Manager
Logic Technology Development

DEG Group Operations

intel Leap ahead

1

Jan. 2007

Intel's Logic Technology Evolution

Process Name:	P1262	P1264	P1266	P1268	P1270
Lithography:	90 nm	65 nm	45 nm	32 nm	22 nm
1st Production:	2003	2005	2007	2009	2011

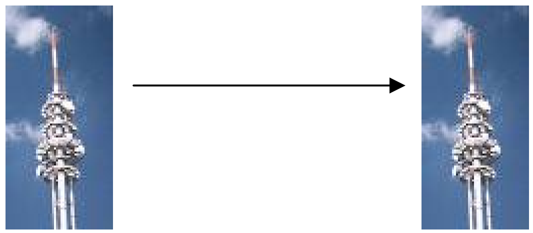
45 / 33 / 22... nm CMOS

vast #s of near-THz transistors

what NEW mm-wave applications will this enable ?

What could you do with a vast # of high-frequency transistors ?

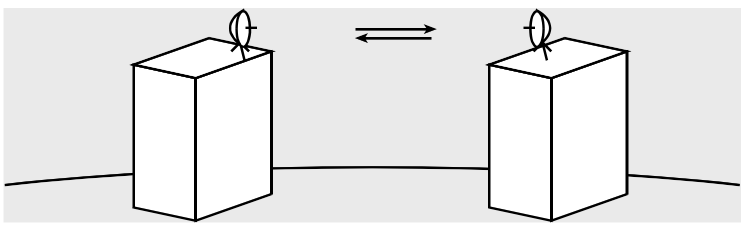
mm-wave array ICs for Gb/s mobile communications



mm-wave Bands → Lots of bandwidth

$$\left(\frac{P_{received}}{P_{transmitted}}\right) = \left(\frac{1}{16\pi^2}\right)\left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

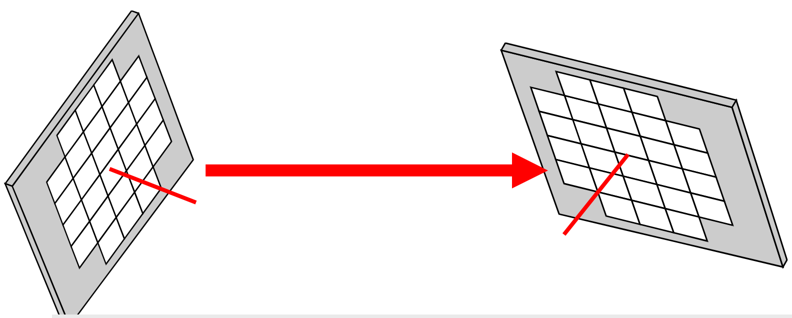
short wavelength→ weak signal →short range



highly directional antenna → strong signal → long range

$$\left(\frac{P_{received}}{P_{transmitted}}\right) = \left(\frac{D_t D_r}{16\pi^2}\right)\left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

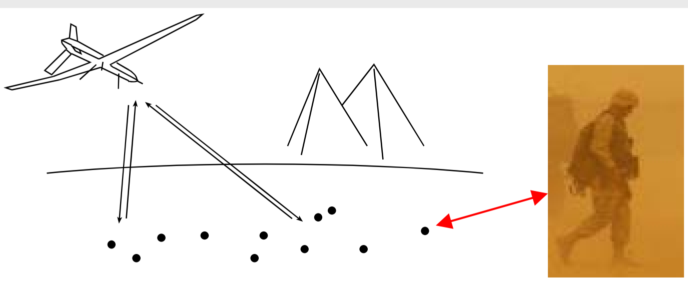
narrow beam → must be aimed →no good for mobile



monolithic beam steering arrays → strong signal, steerable

$$\frac{P_{received}}{P_{transmit}} = \frac{N_{receive} N_{transmit}}{16} \frac{\lambda^2}{R^2} e^{-\alpha R}$$

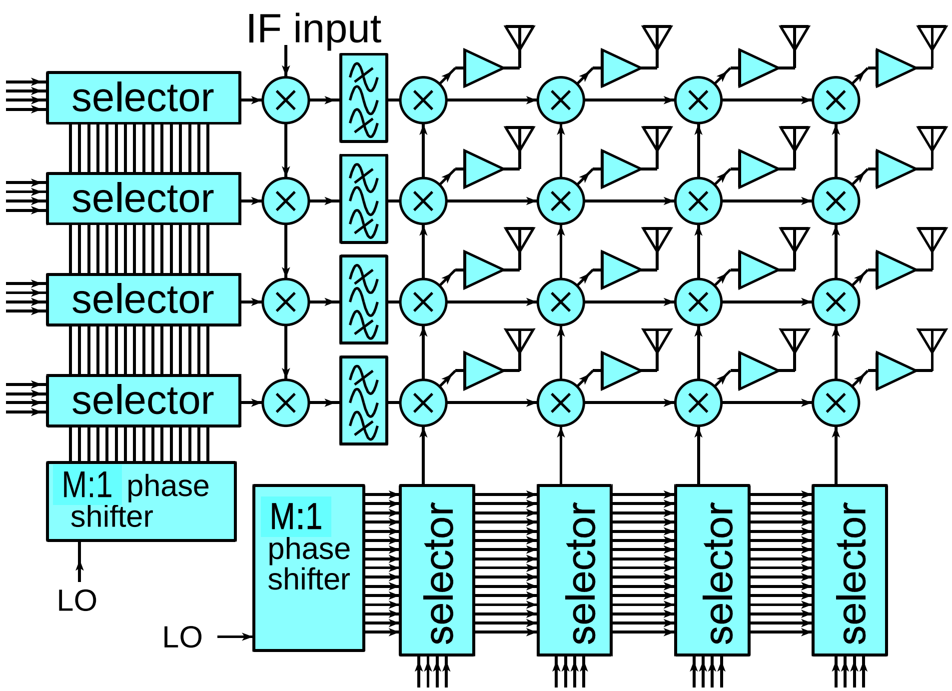
32 x 32 array → 60-90 dB increased SNR →vastly increased range



→ multi-Gigabit mobile communications

Compact, Massive Monolithic mm-Wave Phased Arrays

IC architectures scalable to large array sizes

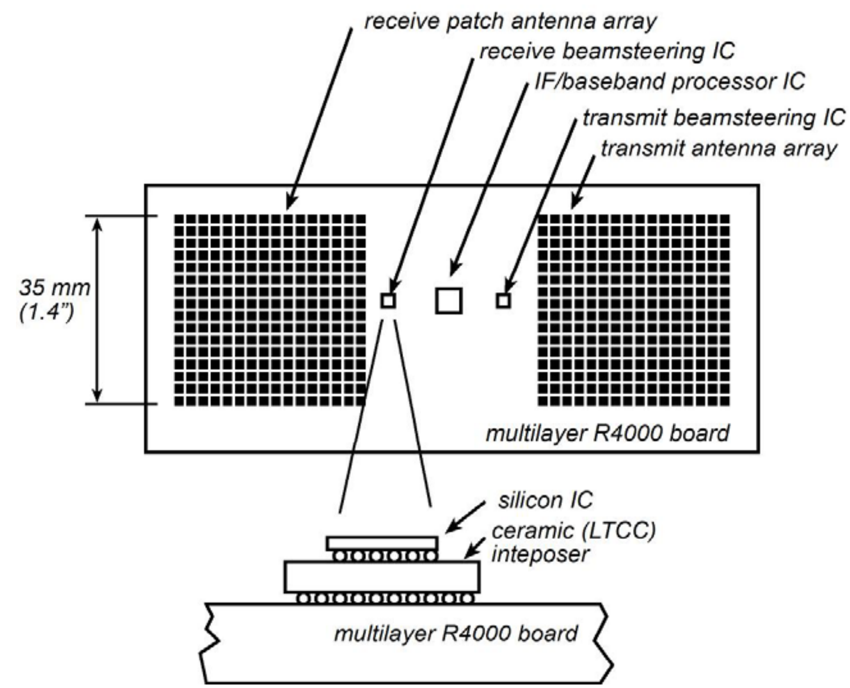


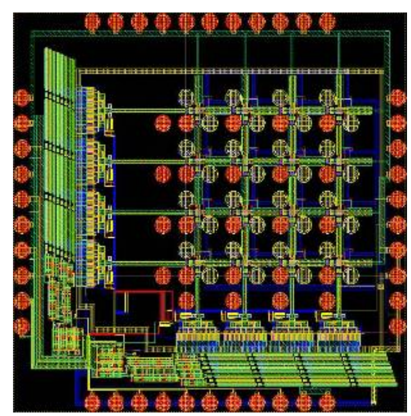
Row-Column Architecture---
1000-element array requires only 60 phase shifters

Mixed-signal IC design
minimal inductive tuning → robust & compact
digital LO phase control → robust & compact
minimal RF signal propagation → robust

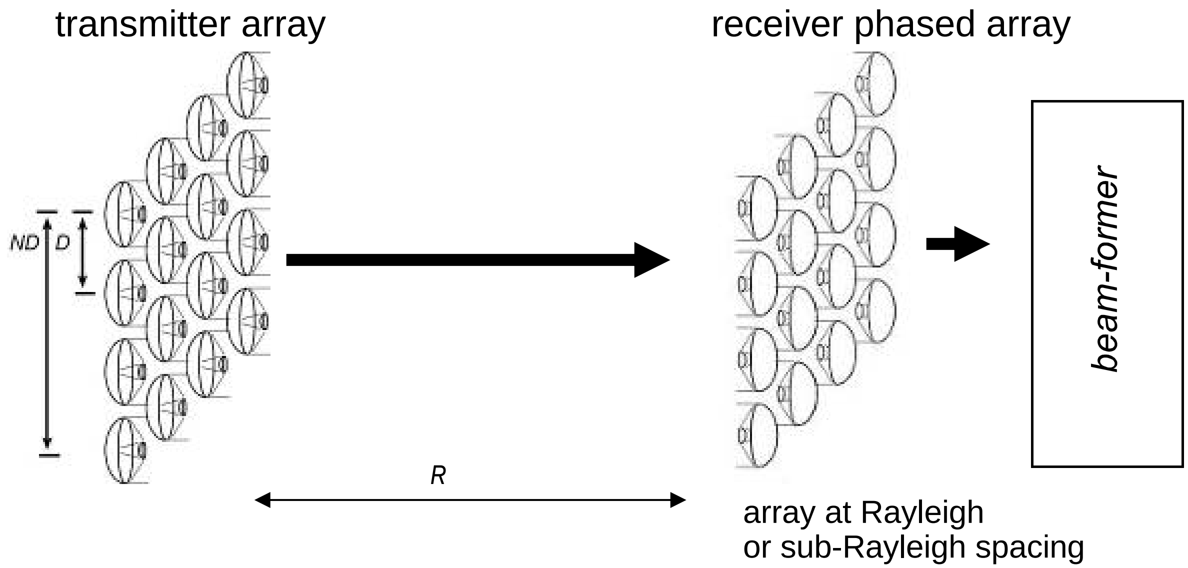
"Digital ICs scale, Analog ICs don't"

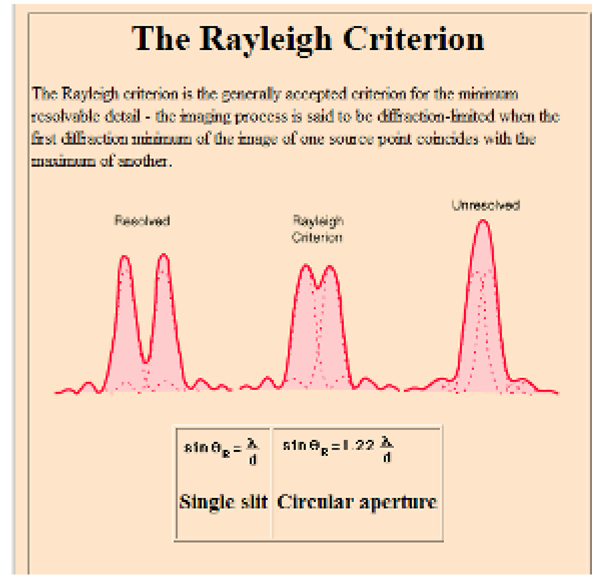
compact circuit-board-based packaging and antennas





mm-wave MIMO → wireless at 160 Gb/s rates





16 wireless communication links, each channel carrying 4QPSK @ 10 Gb/s

Transmitter is N x N elements (N= 4), each transmitting independently

Receiver is N x N phased array, with beamformer imaging on the N^2 transmitters

If element spacings meet Rayleigh criterion, then channels do not interfere

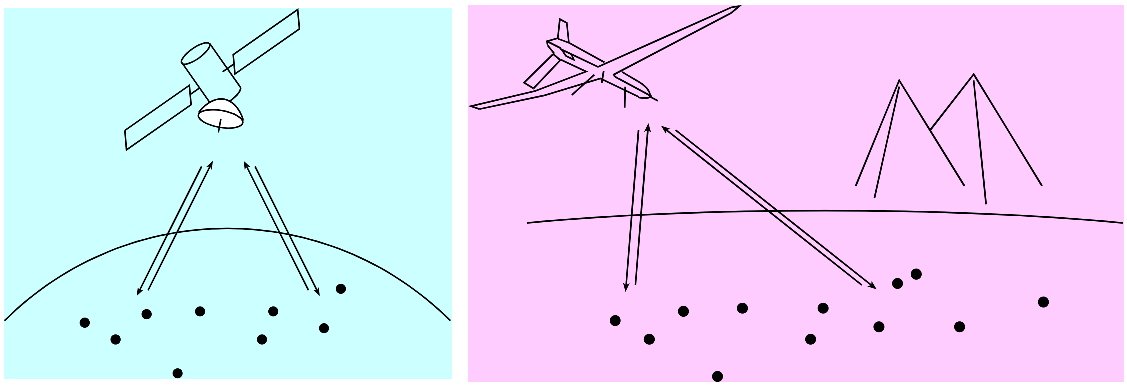
Feasible range exceeds one mile, even in foul weather

Spatial angular separation of adjacent transmitters: $\delta\theta_t = D/R$;

Receive array angular resolution: $\delta\theta_r = \lambda/ND$; to resolve adjacent channels, $\delta\theta_r \le \delta\theta_r \Rightarrow ND = \sqrt{\lambda NR}$

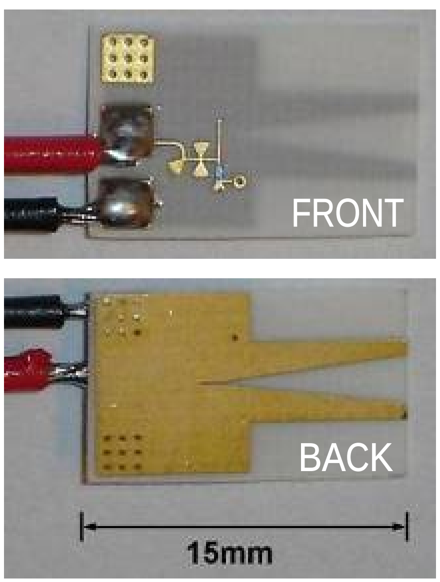
mm-wave CMOS→ Imaging/Radar Sensor Networks

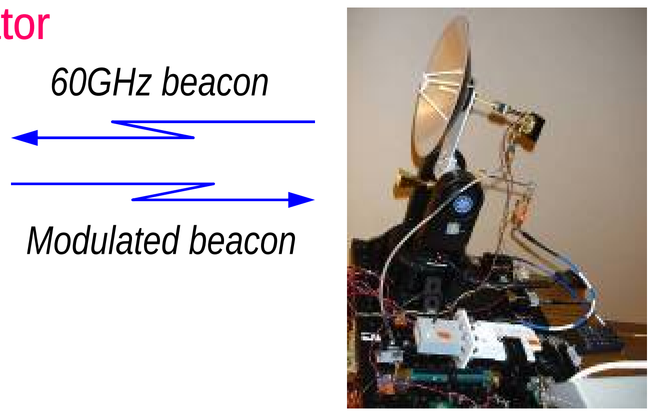
<u>*Data collection aircraft :*</u> *phased array transmitter / receiver*

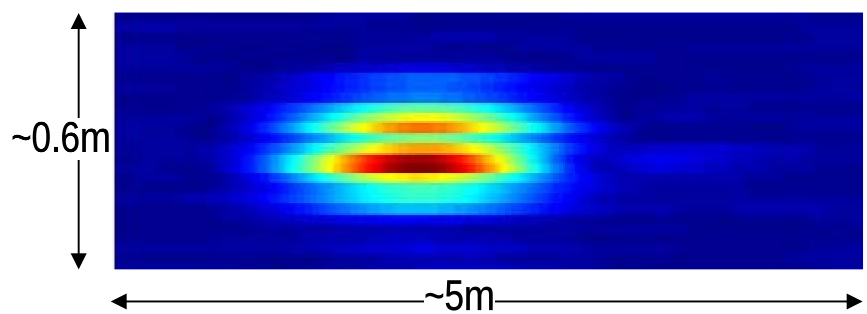


<u>*very simple sensors , mm-wave CMOS*</u>*:*
passive or active transponders;
data modulation.
Range = 10's of km at kb/s rates

Sensor= Antenna + Modulator



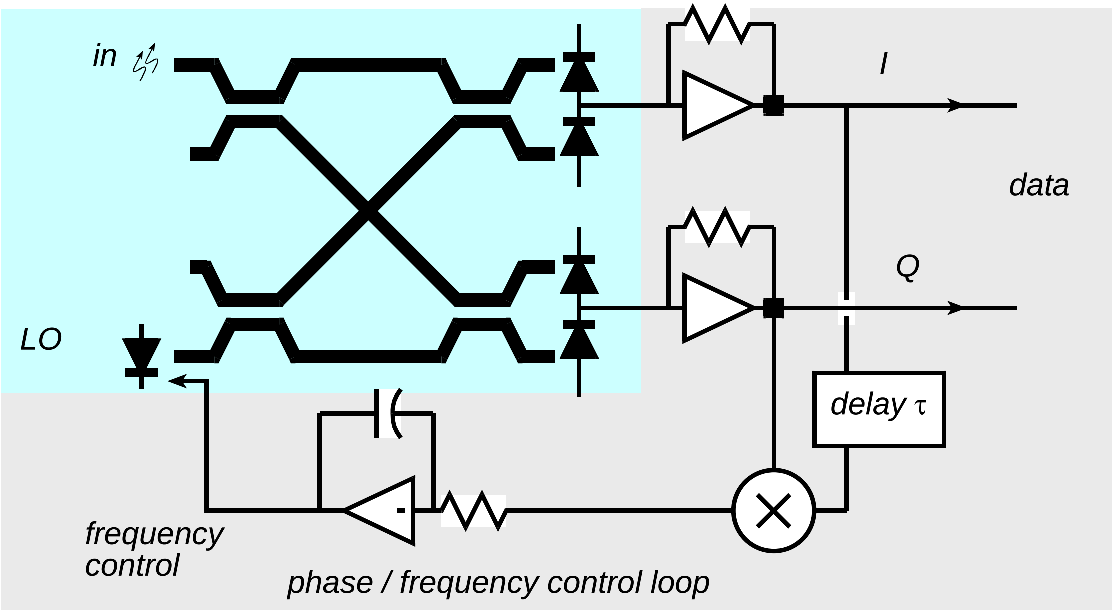




resolving two nearby sensors

--data is also recovered

Compact Phase/Frequency-Locked Optical PLLs



Coherent Optical Receivers

Optical Frequency Synthesis

Convergence of bandwidths:
IC bandwidths > 100 GHz
F-P laser frequency (wavelength) precision ~1000 GHz

O/E PLL with phase / frequency detection:
~200 GHz pull-in range, without scanning
→ direct electrical/optical phase-locking
...even for inexpensive F-P lasers

Compact coherent receivers: QPSK modulation, greatly simplified (DFE/FFE) dispersion compensation
Broad tolerance to LO laser phase noise