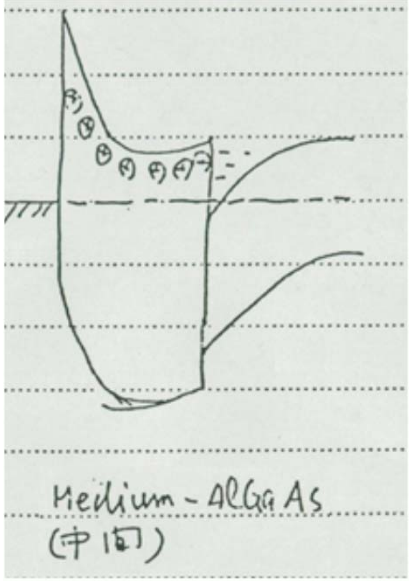
The High-Electron Mobility Transistor
at 30:
Impressive Accomplishments
and Exciting Prospects

J. A. del Alamo

Microsystems Technology Laboratories
MIT

International Conference on
Compound Semiconductor Manufacturing Technology
May 16-19, 2011



Outline

- Introduction
- HEMT electronics
- Modulation-doped structures in physics
- Future prospects

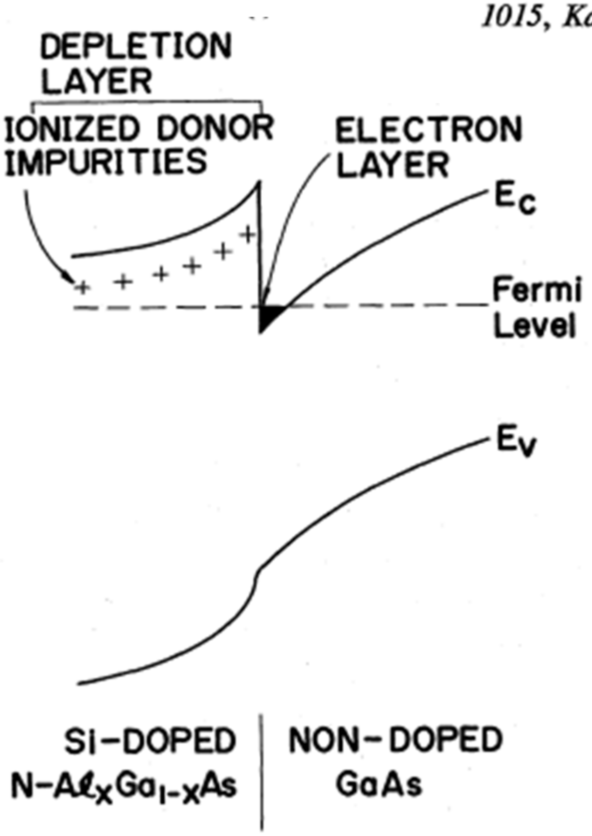
The High Electron Mobility Transistor

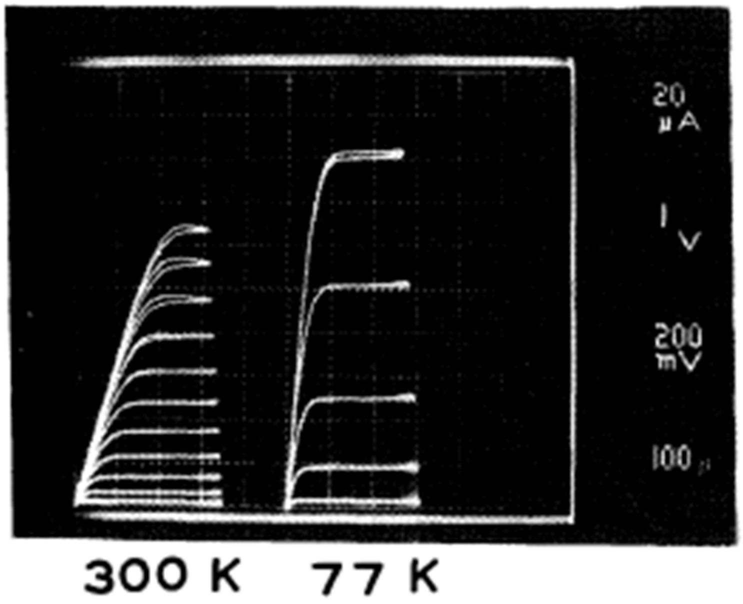
A New Field-Effect Transistor with Selectively Doped GaAs/n-Al$_x$Ga$_{1-x}$As Heterojunctions

Takashi MIMURA, Satoshi HIYAMIZU, Toshio FUJII
and Kazuo NANBU

Fujitsu Laboratories Ltd.,
1015, Kamikodanaka, Nakahara-ku, Kawasaki 211

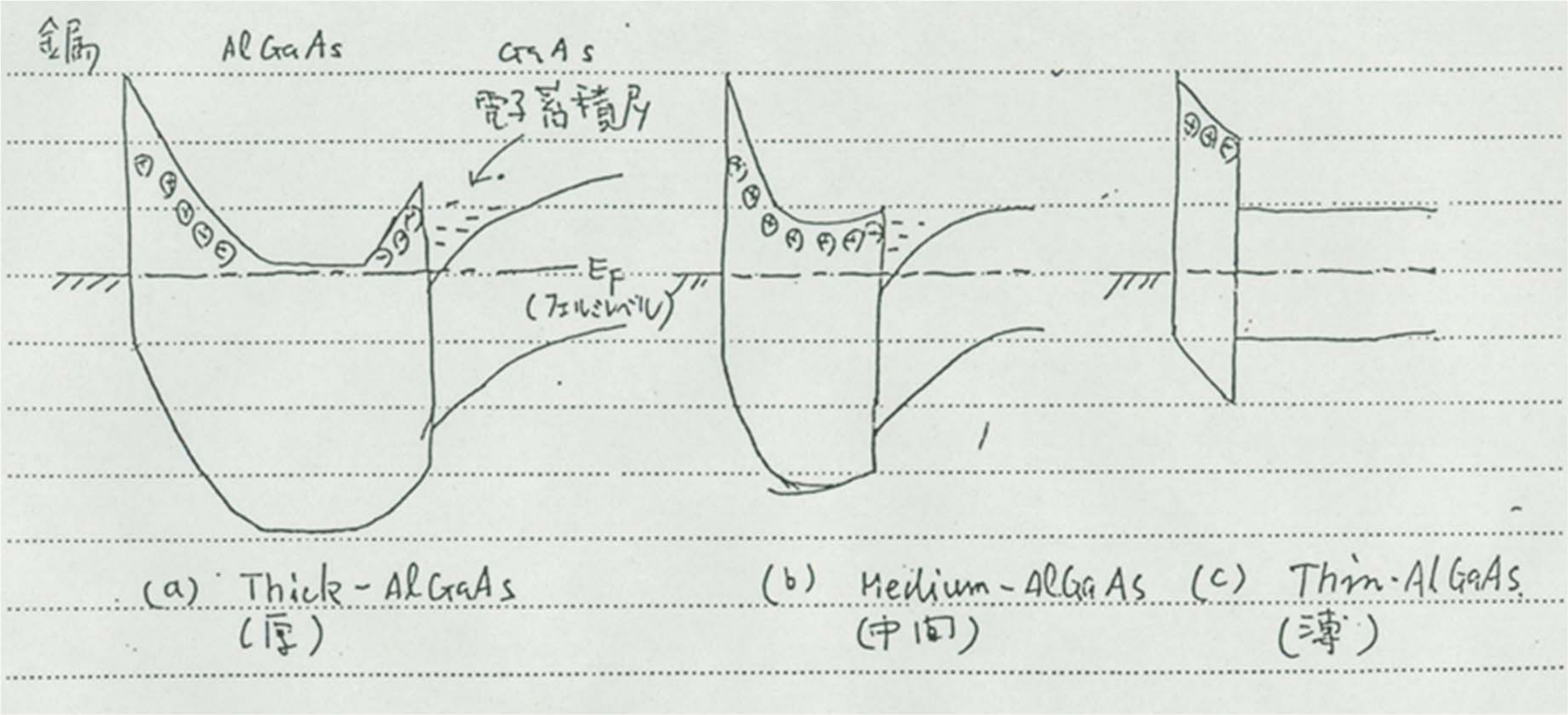
(Received March 24, 1980)





Mimura, JJAPL 1980

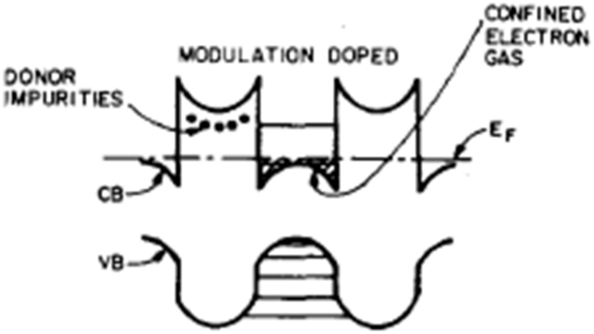
Energy band diagrams in Mimura’s patent application (Aug. 16, 1979)



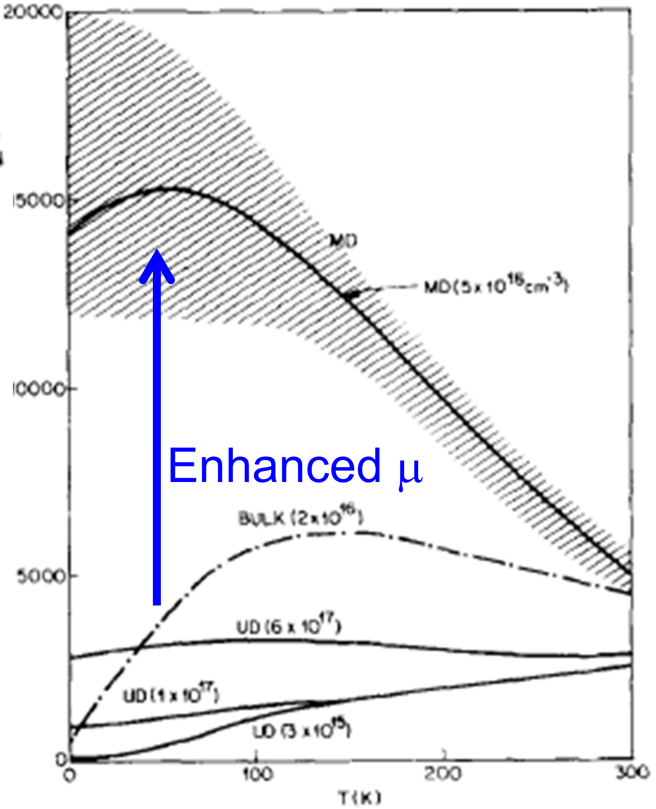
Courtesy of Takashi Mimura (Fujitsu)

Modulation doping

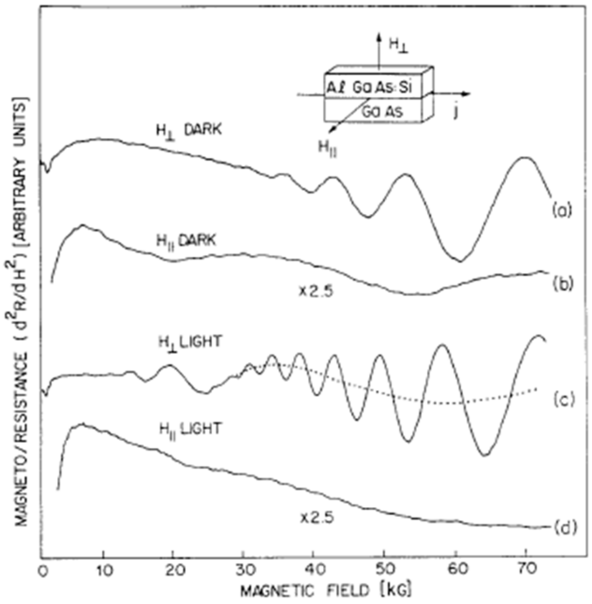
- High electron mobility in modulation-doped AlGaAs/GaAs heterostructures
- 2 DEG at AlGaAs/GaAs interface



Dingle, APL 1978

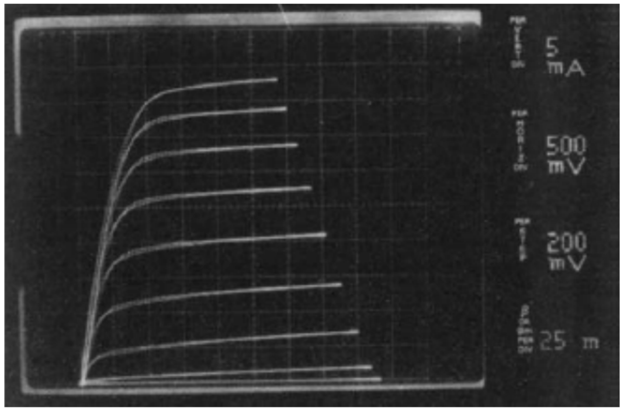


Enhanced μ



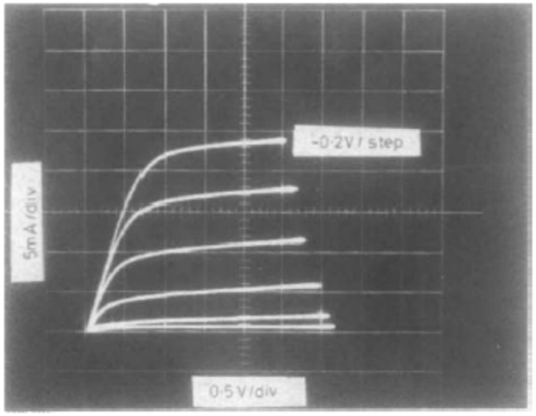
Störmer, Solid St Comm 1979

HEMT by other name...



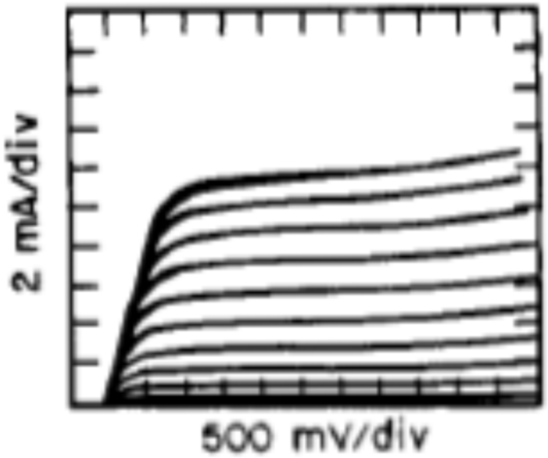
Thomson-CSF:
Two-Dimensional Electron Gas FET (TEGFET)

Laviron, EL 1981



U. Illinois:
Modulation-Doped FET (MODFET)

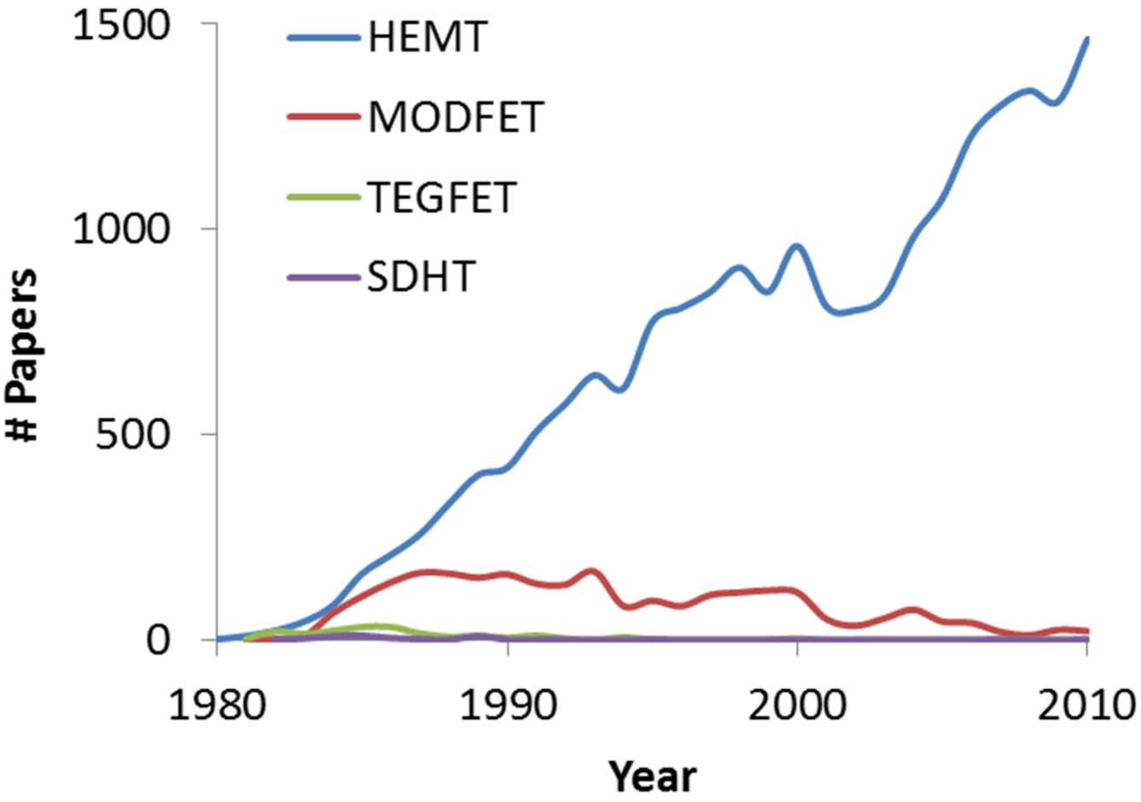
Su, EL 1982



Bell Labs.:
Selectively-Doped Heterojunction Transistor (SDHT)

DiLorenzo, IEDM 1982

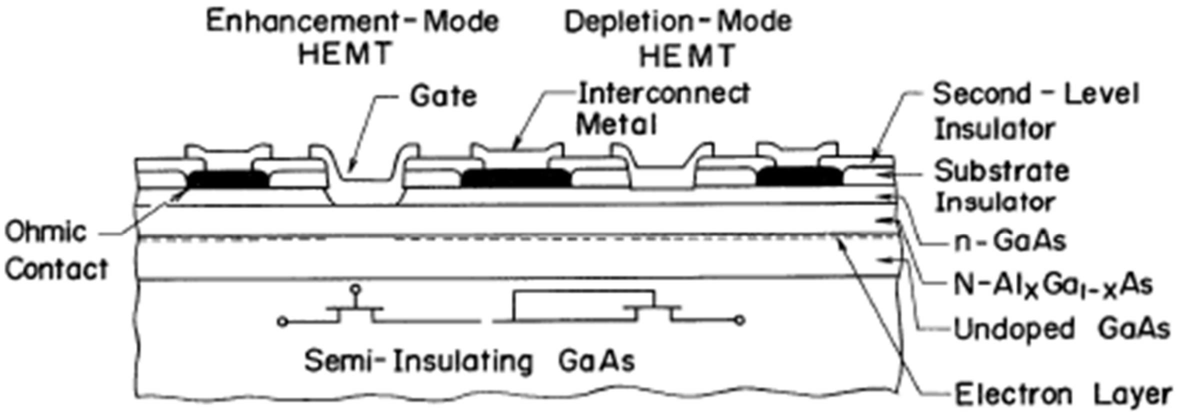
And the winner is...



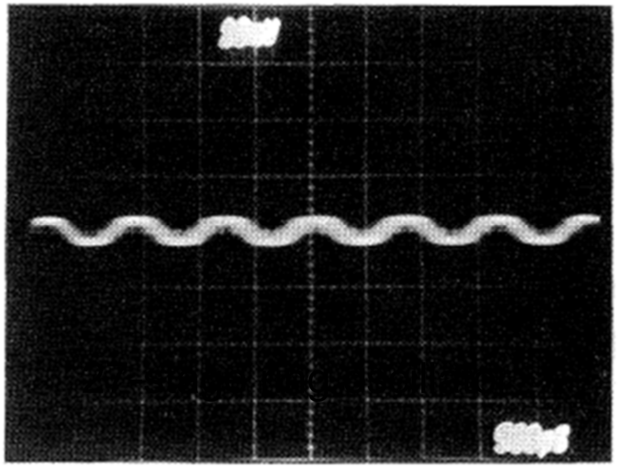
papers in Compendex and Inspec databases with keyword in title, abstract or indexing terms

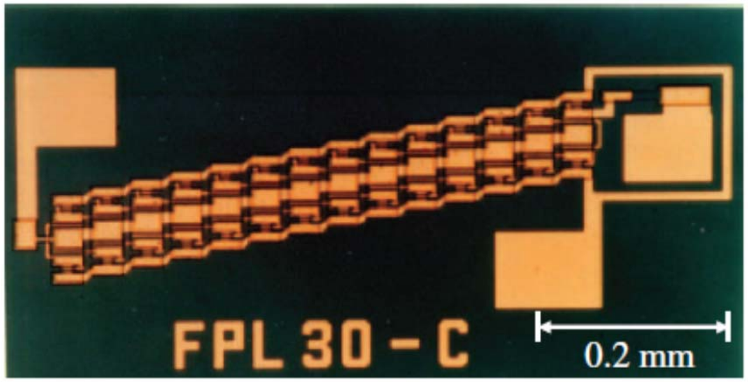
Data courtesy of Angie Locknar (MIT Libraries)

First HEMT IC



E/D logic



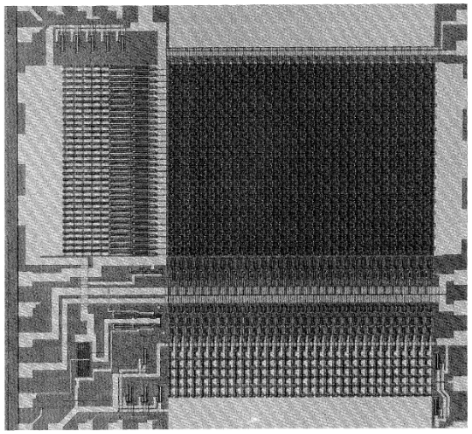


"The switching delay of 17.1 ps is the lowest of all the semiconductor logic technologies reported thus far."

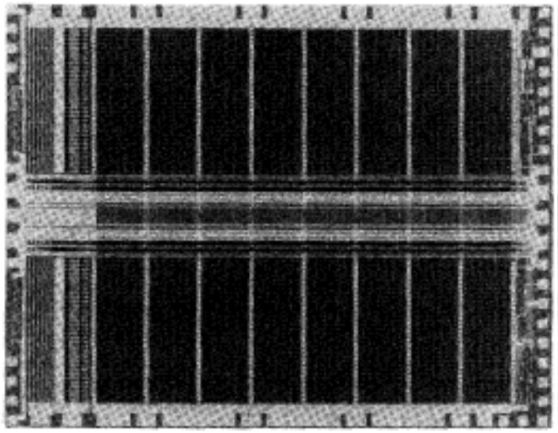
Mimura, JJAPL 1981

"HEMT technology is presenting new possibilities for high-speed low-power very-large-scale-integration."

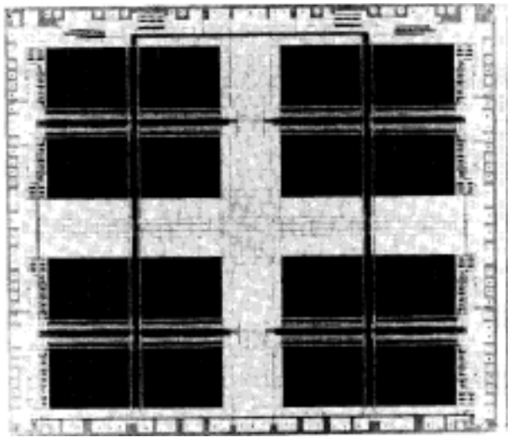
HEMT ICs ride Moore's Law



1 Kb SRAM



16 Kb SRAM



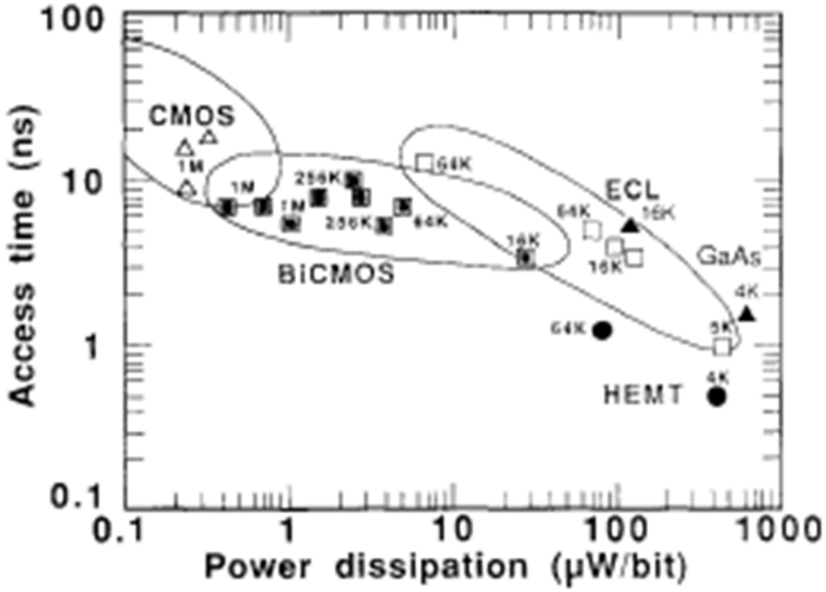
64 Kb SRAM

1984: 1 Kb SRAM (7,244 HEMTs, 8.7 mm^2)

1984: 4 Kb SRAM (26,864 HEMTs, 21 mm^2)

1987: 16 Kb SRAM (107,519 HEMTs, 24 mm^2)

1991: 64 Kb SRAM (>462,000 HEMTs, 48 mm^2)



Watanabe, TED 1987

Abe, JSSC 1991

Suzuki, JSSC 1991

Abe, JVST1987

First HEMT LNA

20 GHz 4-stage HEMT LNA (1983)

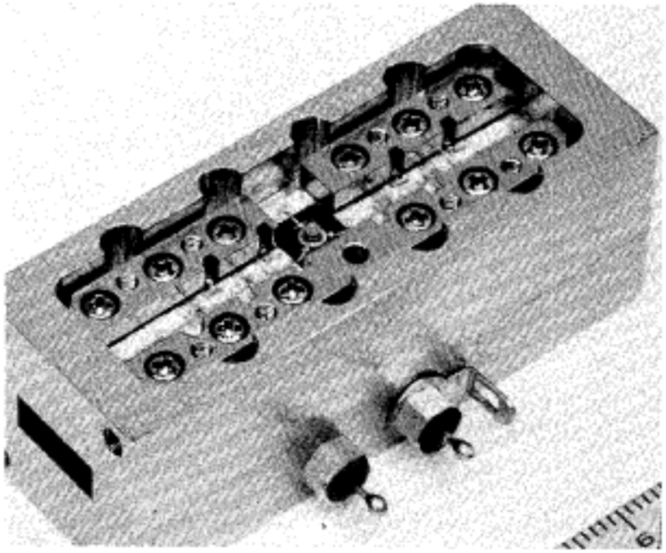
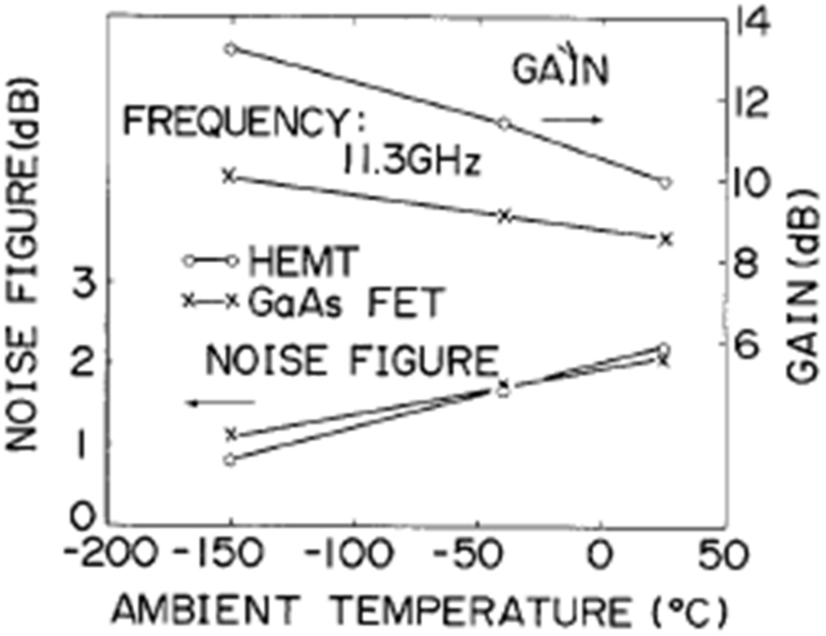


FIGURE 4—A 20GHz 4-stage HEMT amplifier.

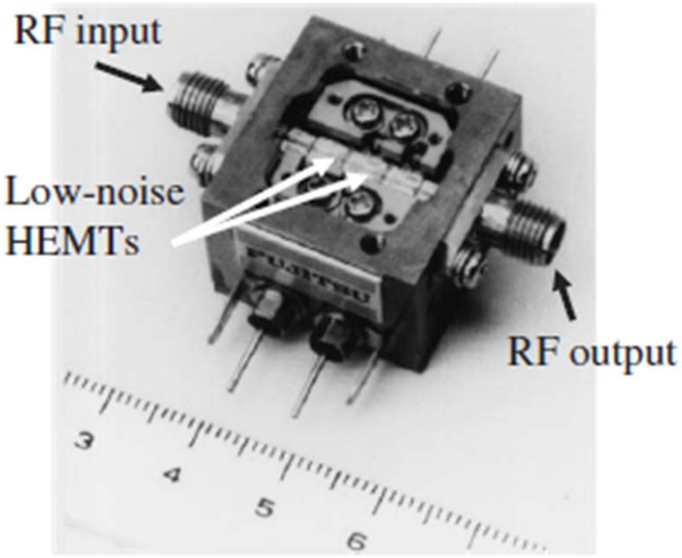


Niori, ISSCC 1983

Great improvement in noise characteristics as T↓

Early commercial applications

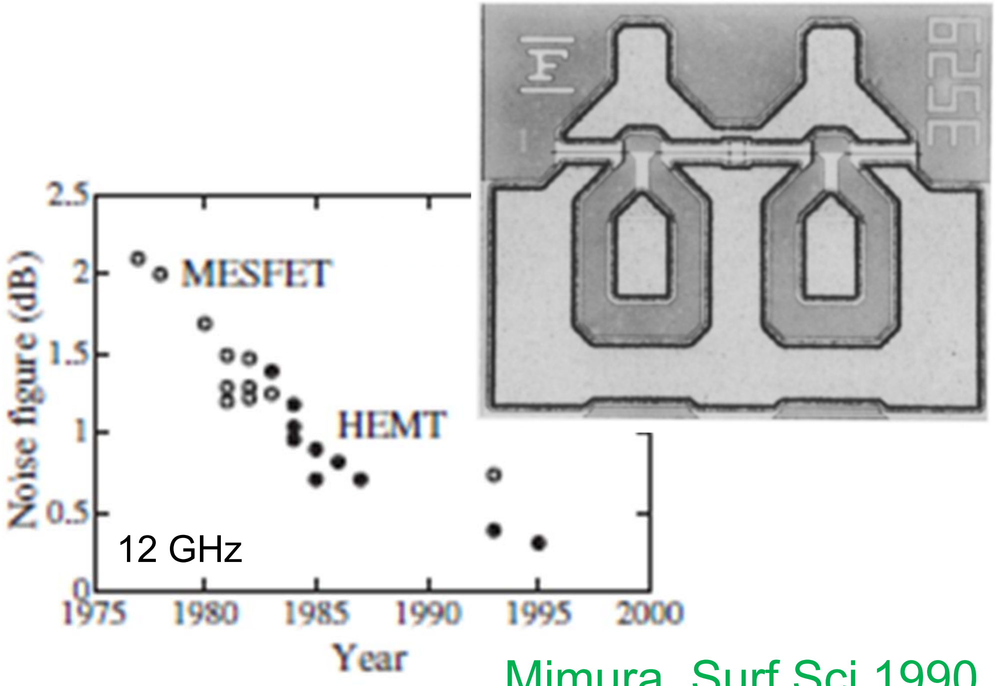
First commercial HEMT product: cryogenic low-noise amplifier at Nobeyama Radio Observatory (1985)



Mimura, JJAP 2005

Used to discover new interstellar molecule C_6H in Taurus Molecular Cloud (1986)

First mass market product: 0.25 µm GaAs HEMTs for LNA in DBS receiver (1987)

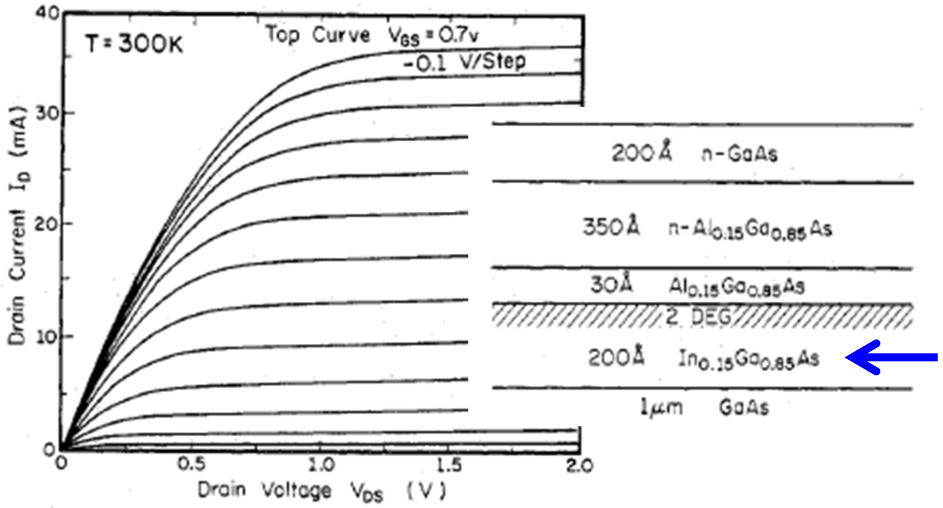


Mimura, Surf Sci 1990

By 1988, world wide production of HEMT receivers reached 20 million/year

Delta-doped pseudomorphic HEMT

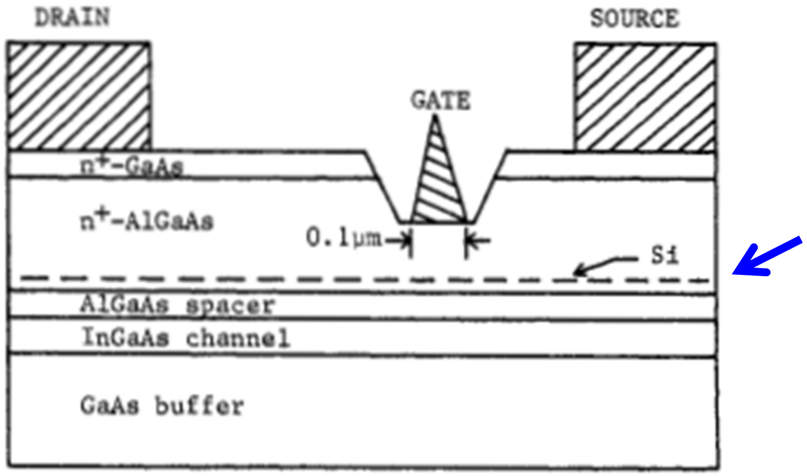
Pseudomorphic HEMT



Ketterson, EDL 1985

- Motivation: lower x in $Al_xGa_{1-x}As$ to avoid carrier freeze-out
- Enhanced transport in InGaAs
- Large ΔE_c → enhanced current

Delta doping



Chao, IEDM 1987

- Enabled barrier thickness scaling → improved transconductance and scalability
- Enhancement of breakdown voltage

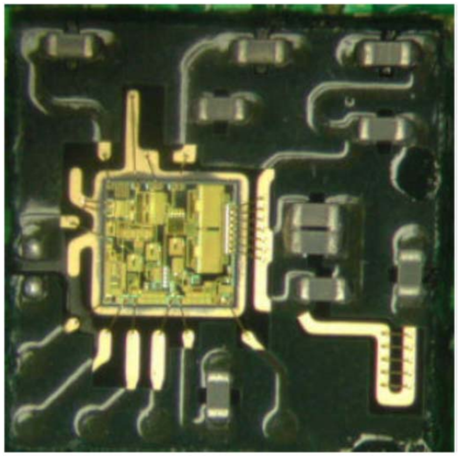
PHEMT ICs

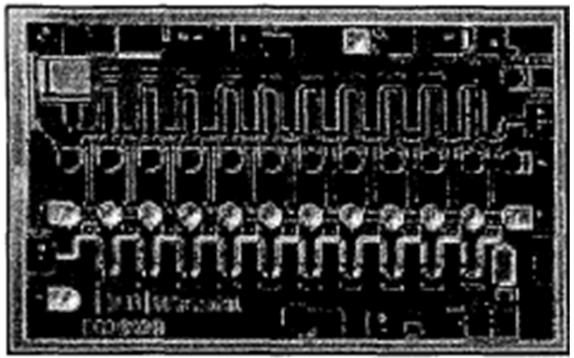

Saturday, February 26, 2011

TriQuint and Skyworks Power iPhone 5

UMTS-LTE PA module

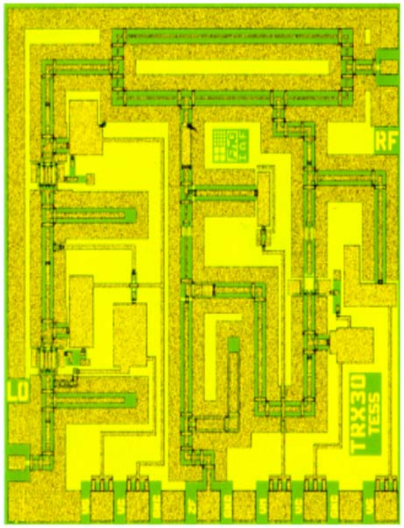
Chow, MTT-S 2008





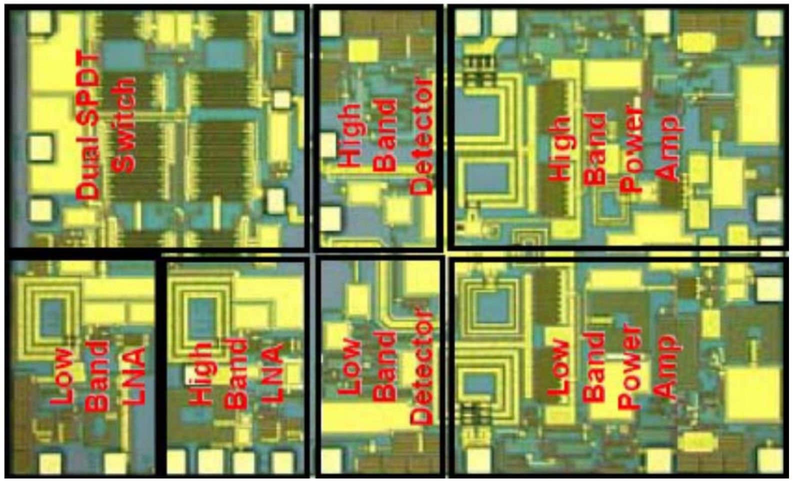
40 Gb/s modulator driver

Carroll, MTT-S 2002



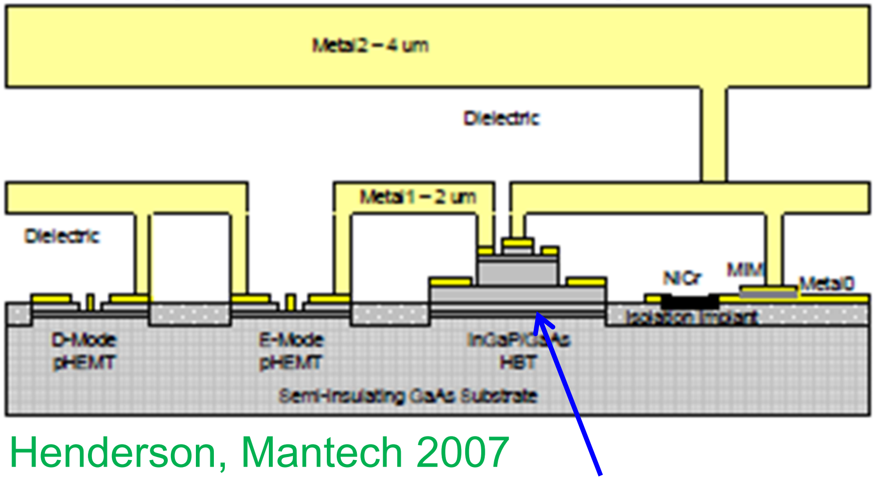
77 GHz transceiver

Tessmann, GaAs IC 1999



Single-chip WLAN MMIC, Morkner, RFIC 2007

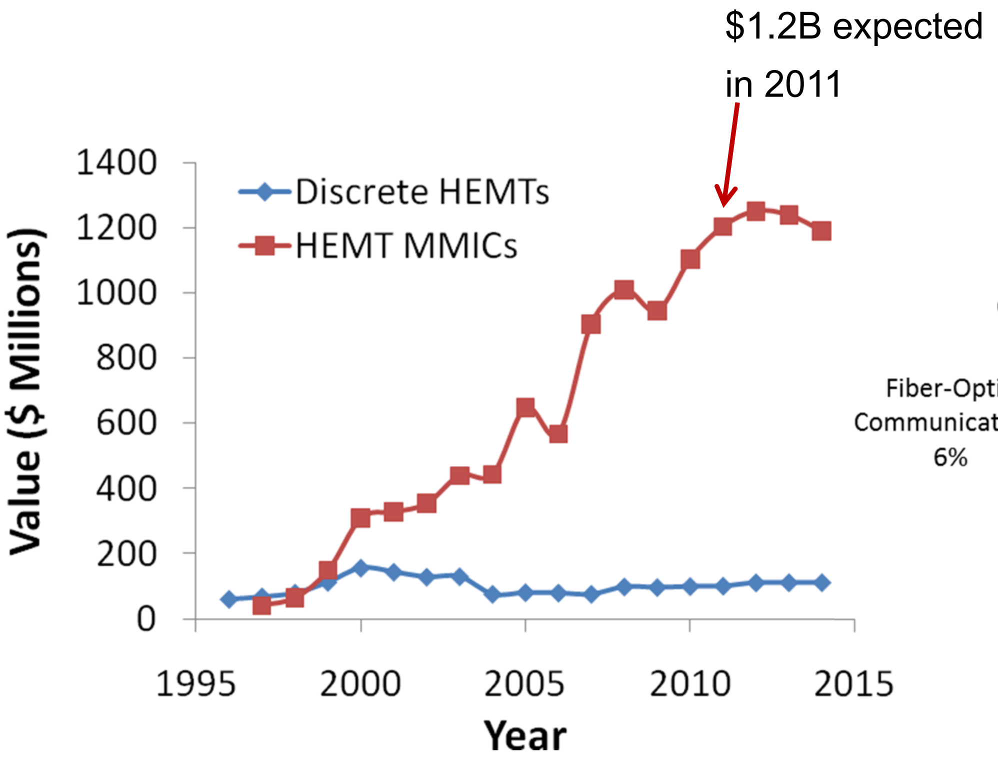
Bipolar/E-D PHEMT process

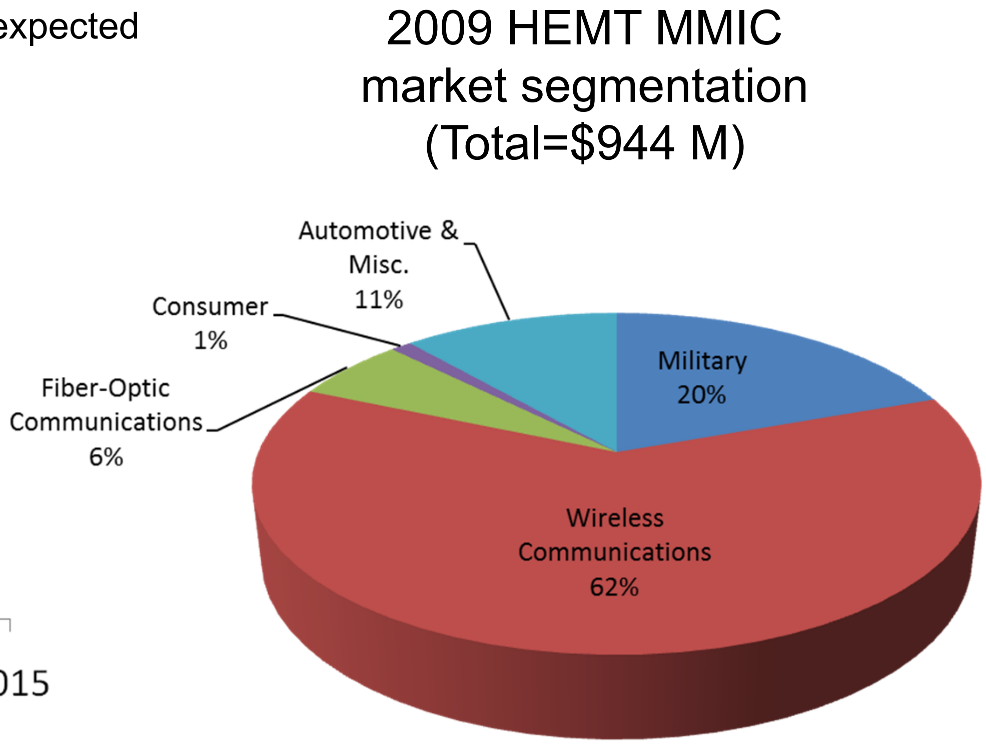


Henderson, Mantech 2007

Single MOCVD growth

HEMT markets



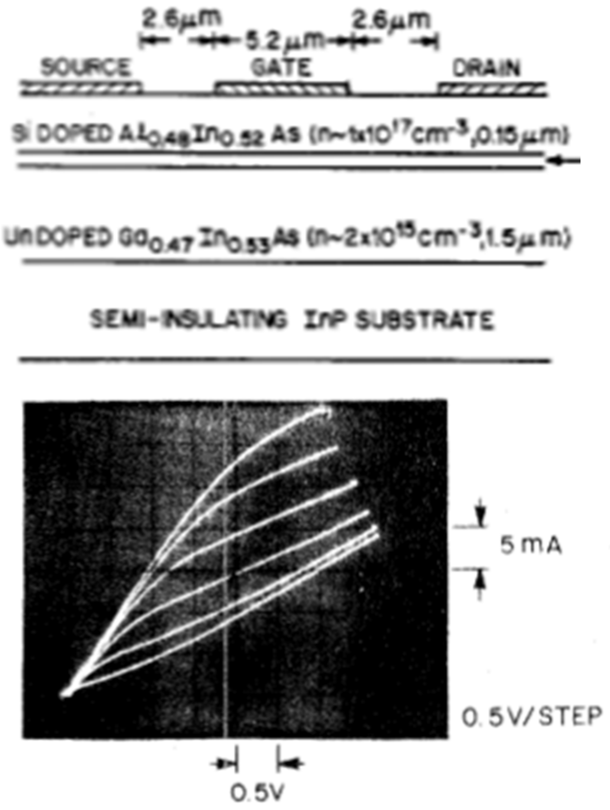


- Biggest market: wireless communications
- Biggest applications: cell phone handsets, WLAN, base stations and CATV

Data courtesy of Eric Higham (Strategy Analytics)

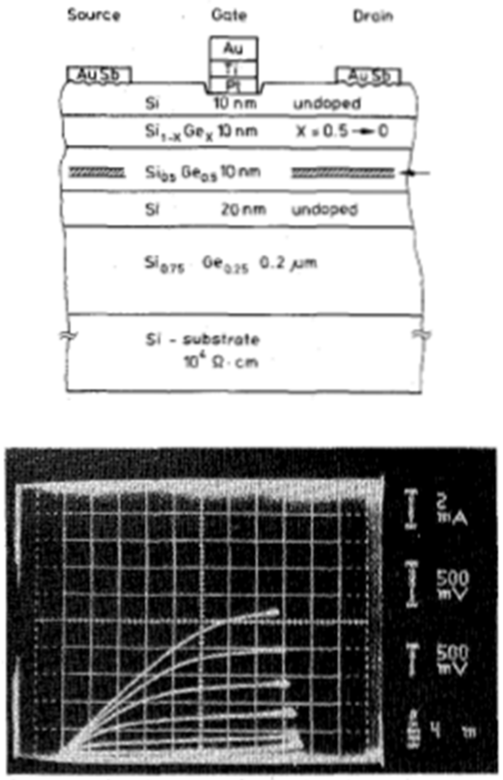
HEMTs in other material systems

InAlAs/InGaAs on InP



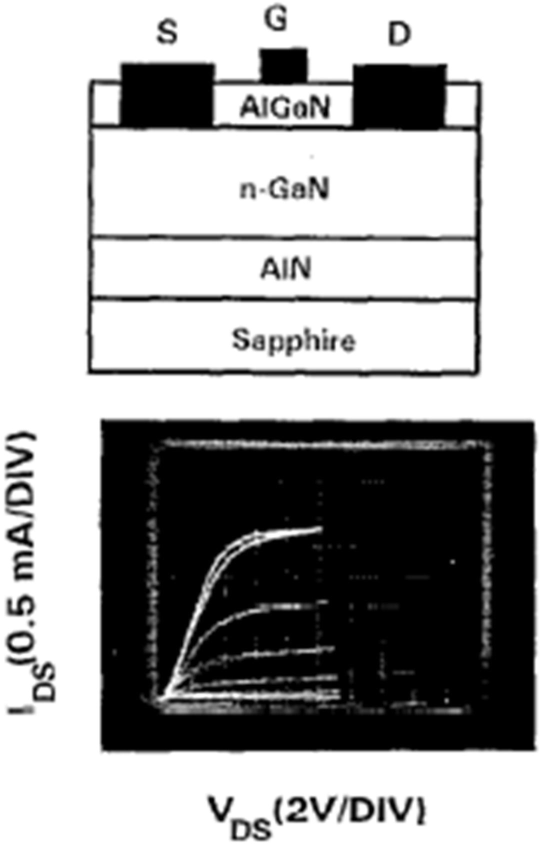
Chen, EDL 1982

SiGe/Si



Daembkes, TED 1986

AlGaN/GaN

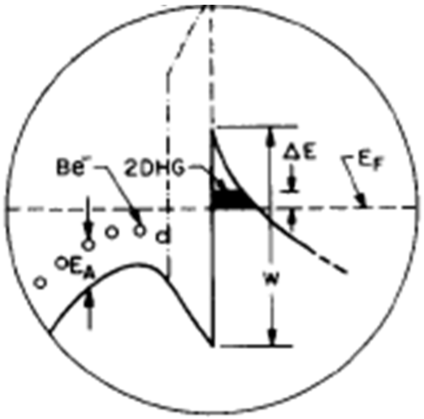


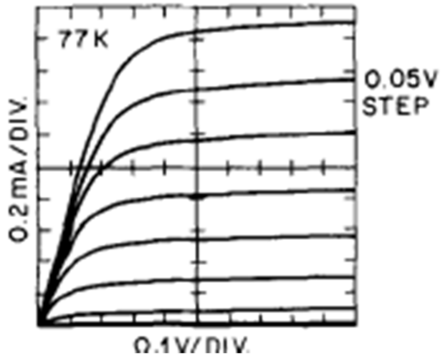
Khan, APL 1993

Also: AlSb/InAs, AlInSb/InSb, etc

High *Hole* Mobility Transistors

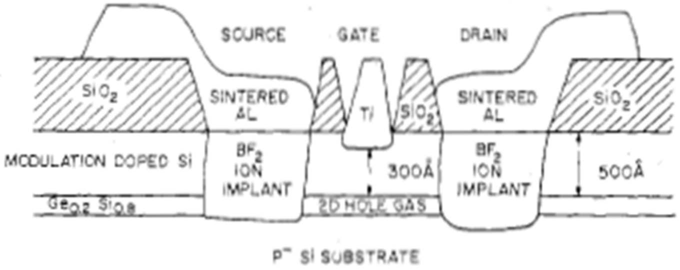
AlGaAs/GaAs

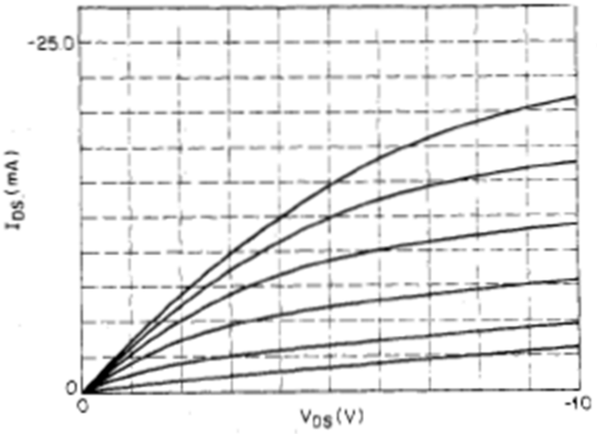




Störmer, APL 1984

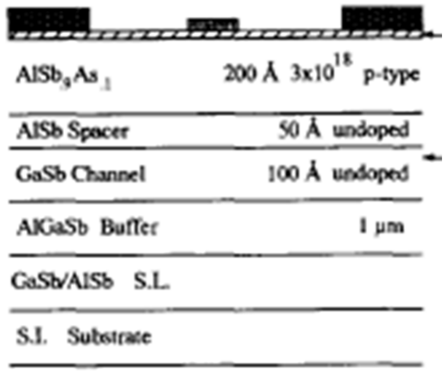
Si/SiGe

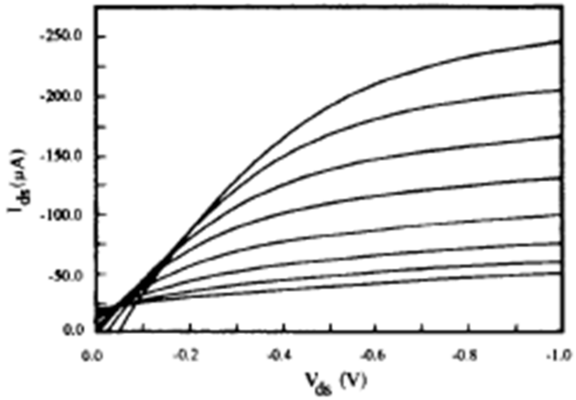




Pearsall, EDL 1986

AlSbAs/GaSb



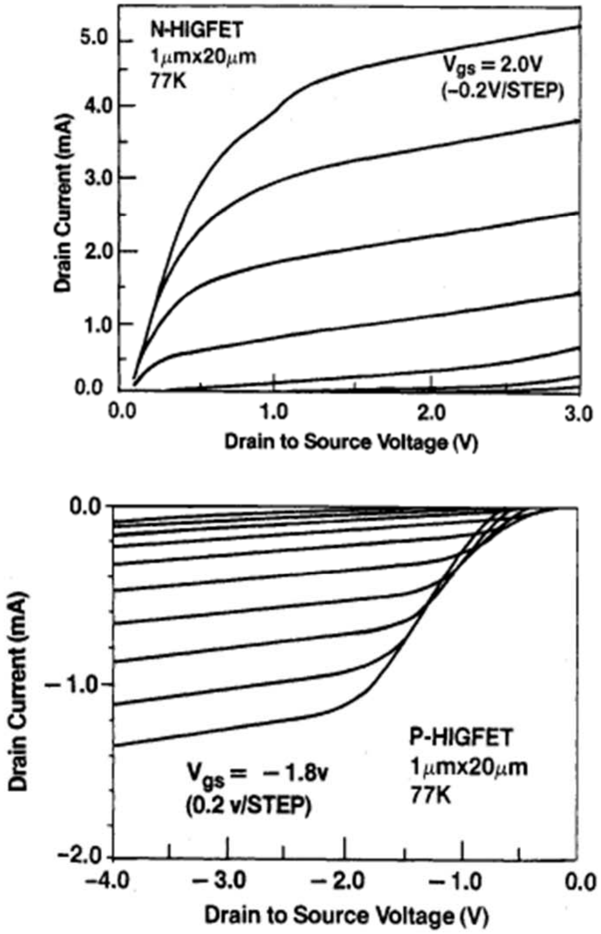


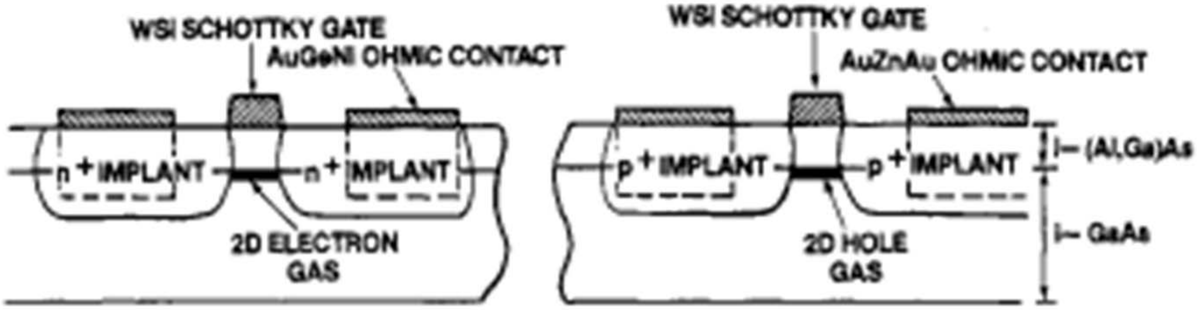
Luo, EDL 1990

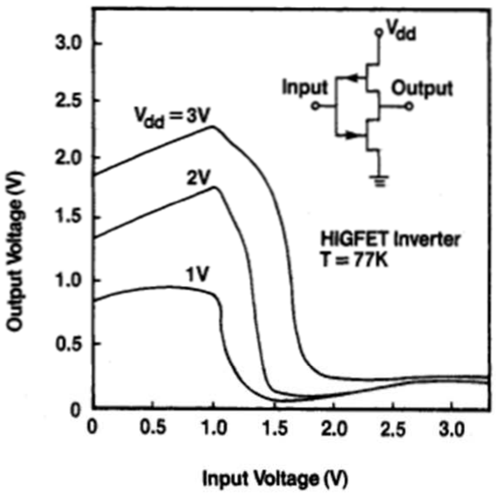
Also: AlGaAs/InGaAs, InAlAs/InGaAs, AlGaSb/InGaSb, InGaN/GaN, etc

Complementary HEMT / HHMT ICs

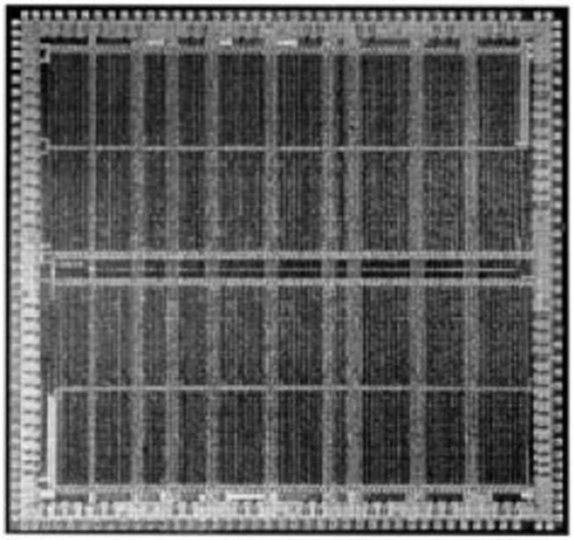
AlGaAs/GaAs system







Cirillo, IEDM 1985



171,000 transistor 16-channel signal distribution system

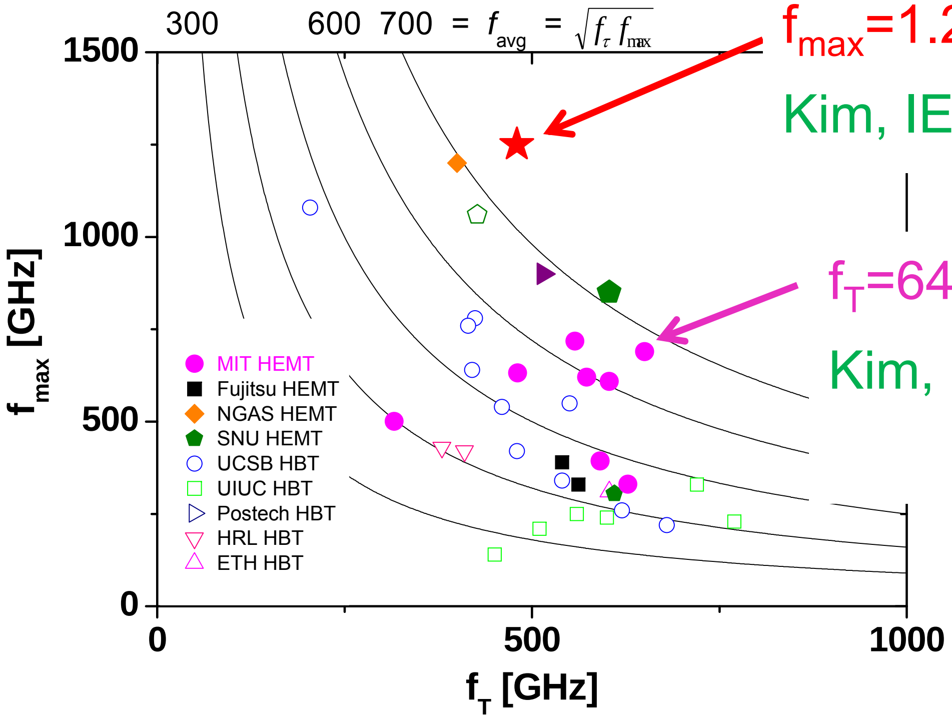
Also: InAlAs/InGaAs system

Brown, Trans VLSI Syst 1998

InAlAs/InGaAs HEMTs on InP

Uniqueness: very high mobility and velocity

→ record frequency response at very low voltage



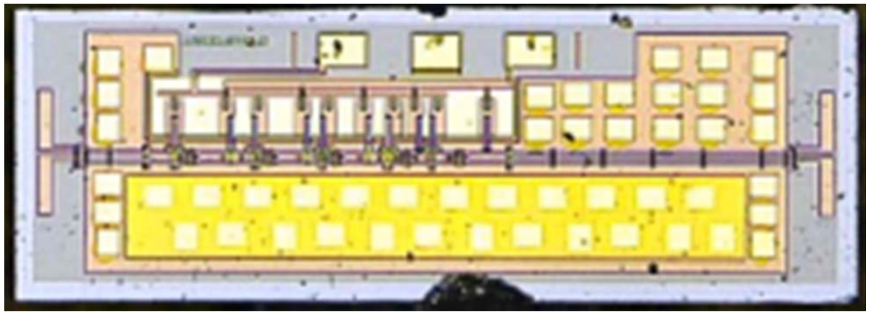
f_{max}=1.25 THz @ 0.8 V

Kim, IEDM 2010

f_T=644 GHz, f_{max}=681 GHz @ 0.5 V

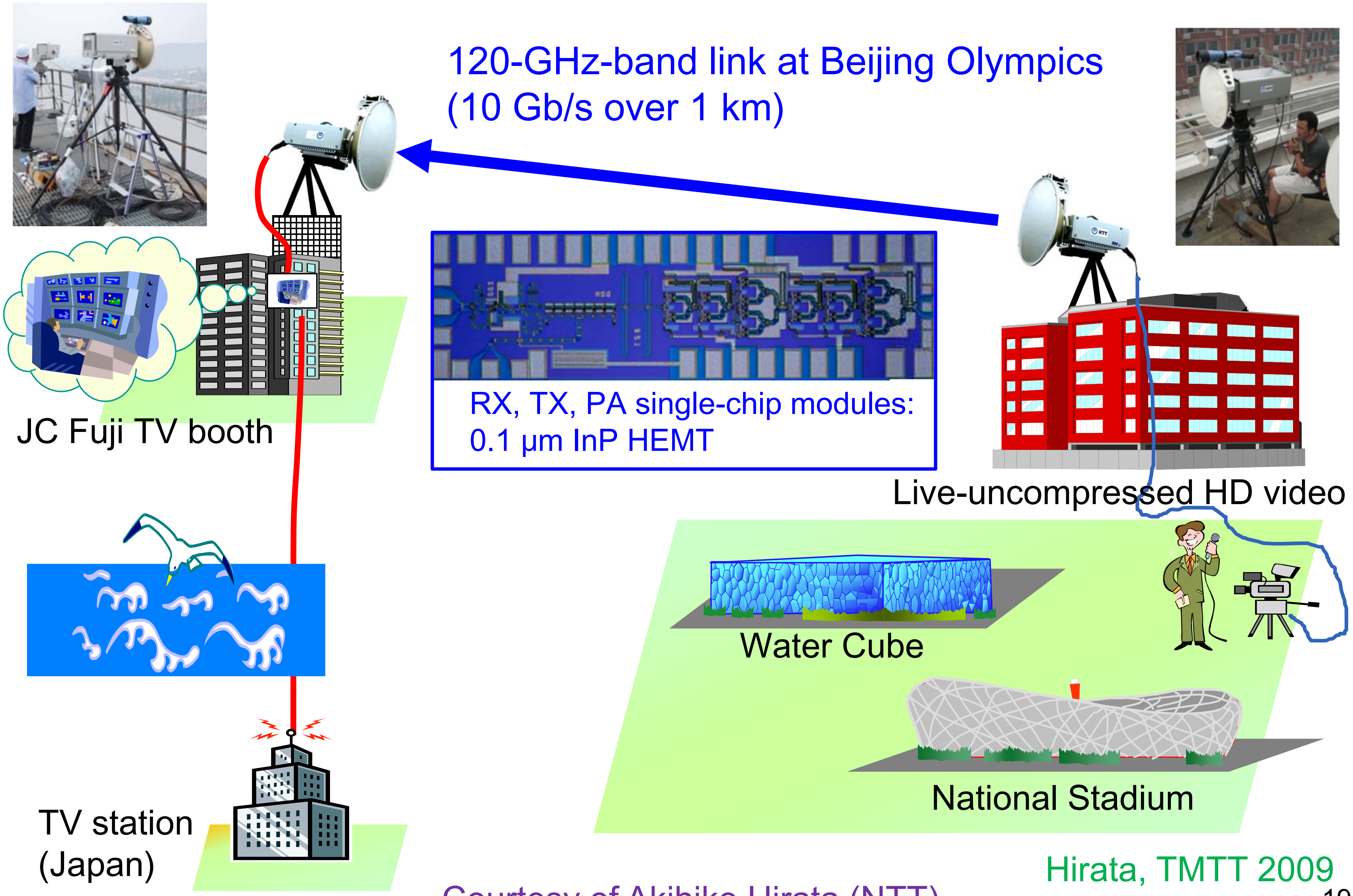
Kim, EDL 2010

5-stage 480 GHz amp (G=11.7 dB)



Deal, MWCL 2010

InAlAs/InGaAs HEMT mmw ICs



120-GHz-band link at Beijing Olympics
(10 Gb/s over 1 km)

JC Fuji TV booth

RX, TX, PA single-chip modules:
0.1 µm InP HEMT

Live-uncompressed HD video

Water Cube

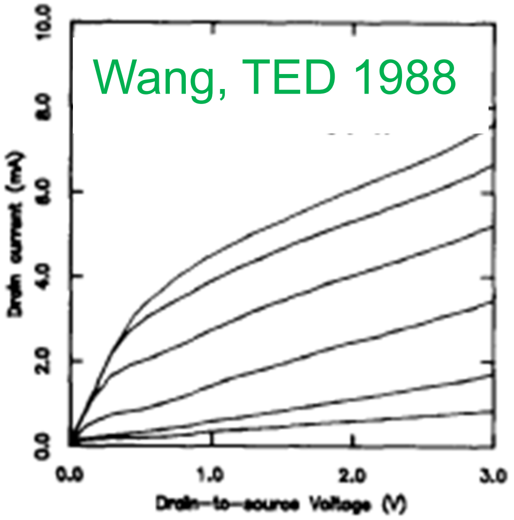
National Stadium

TV station
(Japan)

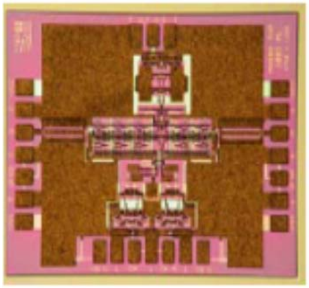
Hirata, TMTT 2009

Courtesy of Akihiko Hirata (NTT)

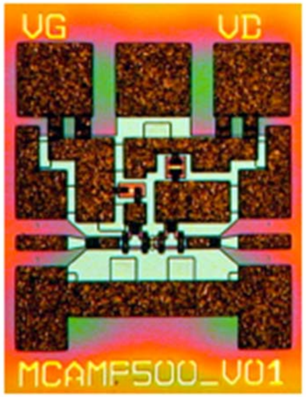
InAlAs/InGaAs Metamorphic HEMTs *on GaAs*



Wang, TED 1988



80 Gb/s multiplexer IC

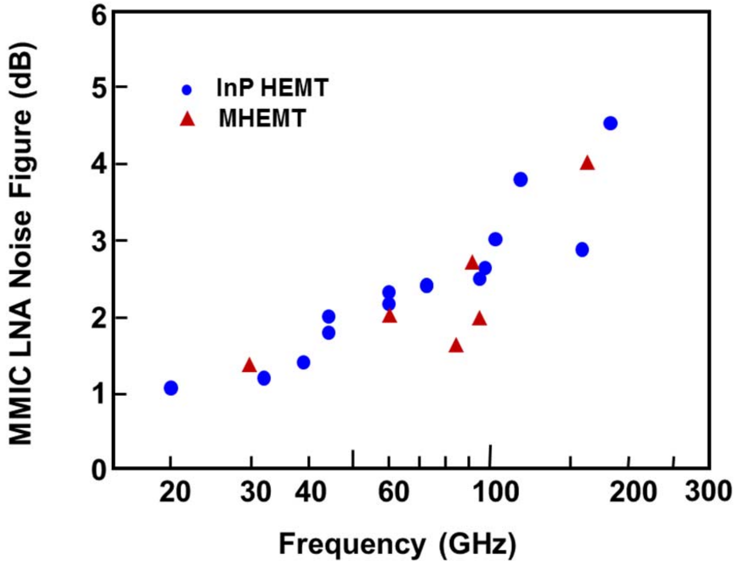


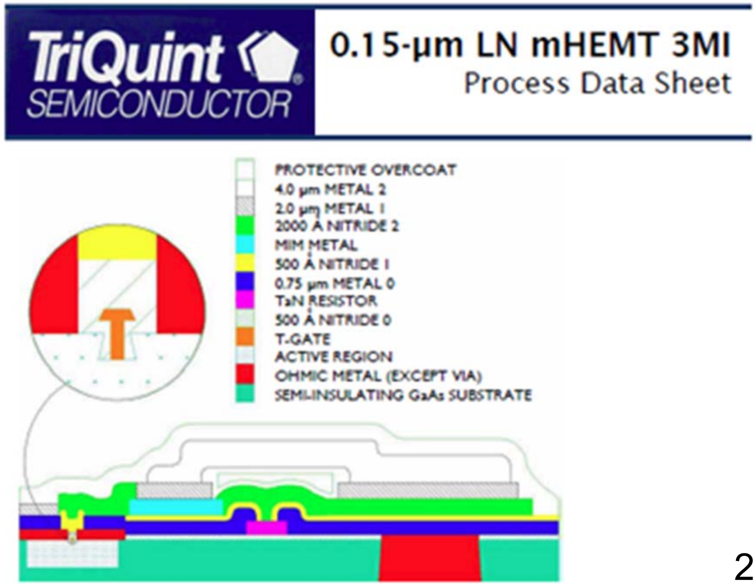
Single-stage 500 GHz LNA (G=3.3 dB)

Wurfl, GAAS 2004

Tessmann, CSIC 2010

LNA NF vs. f





TriQuint SEMICONDUCTOR

0.15-µm LN mHEMT 3MI

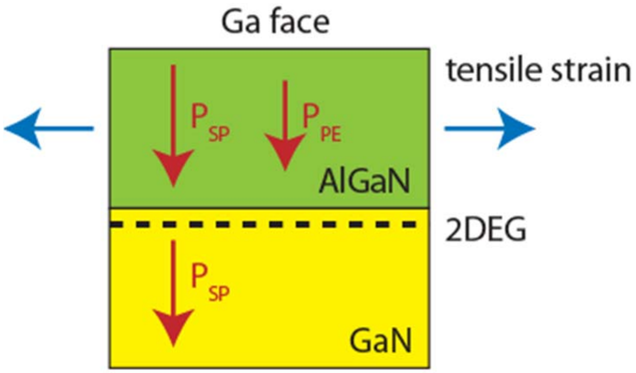
Process Data Sheet

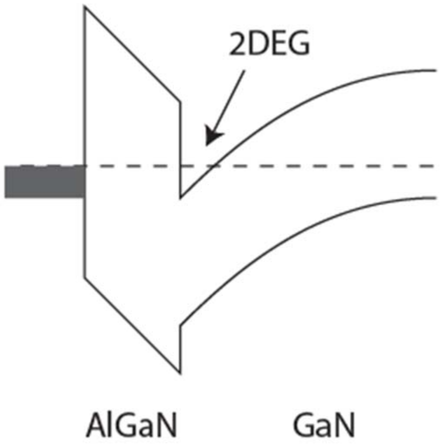
PROTECTIVE OVERCOAT
4.0 µm METAL 2
2.0 µm METAL 1
2000 Å NITRIDE 2
MIM METAL
500 Å NITRIDE 1
0.75 µm METAL 0
TaN RESISTOR
500 Å NITRIDE 0
T-GATE
ACTIVE REGION
OHMIC METAL (EXCEPT VIA)
SEMI-INSULATING GaAs SUBSTRATE

- Comparable performance to InP substrate
- Improved manufacturability
- Lower cost
- Well established packaging technology

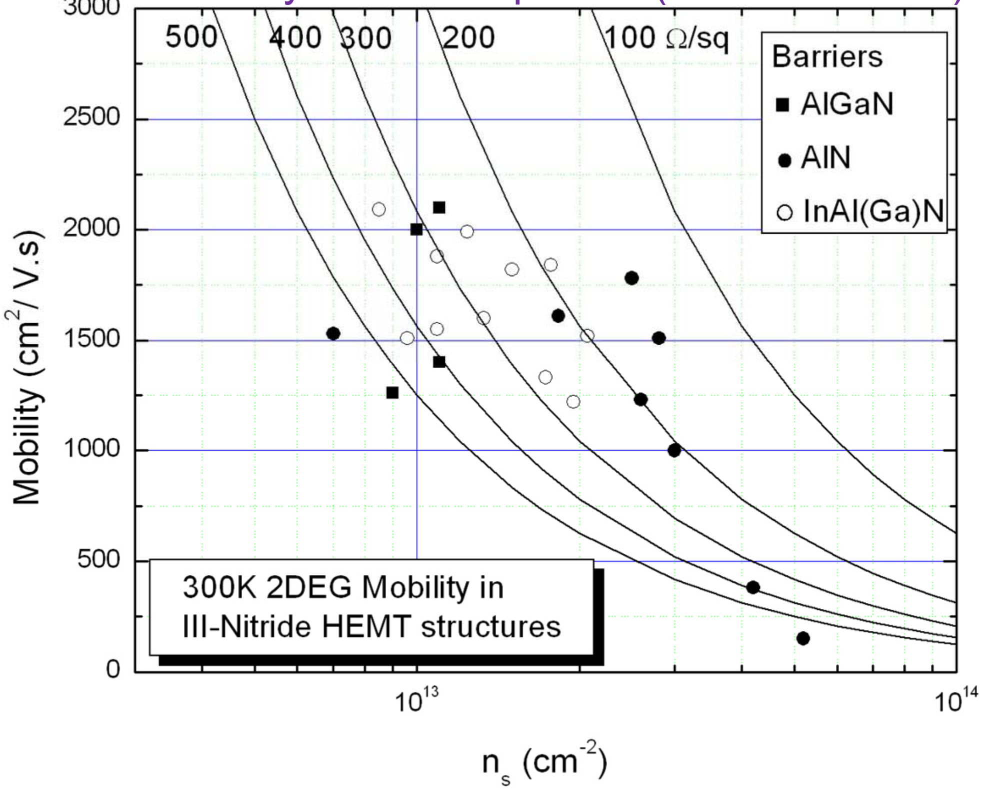
LNA data courtesy of Phillip Smith (BAE Systems)

Polarization doping in Nitrides





Courtesy of Debdeep Jena (U. Notre Dame)

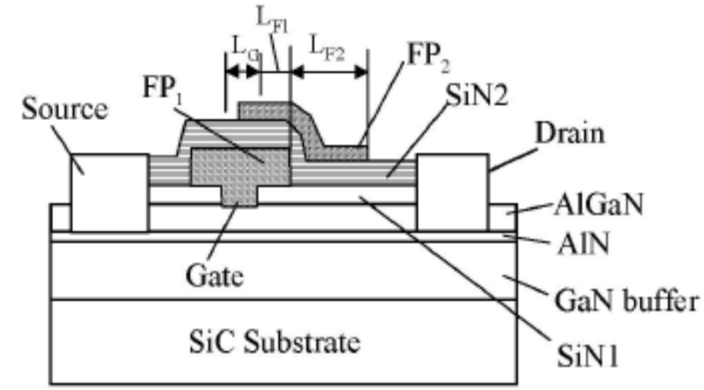


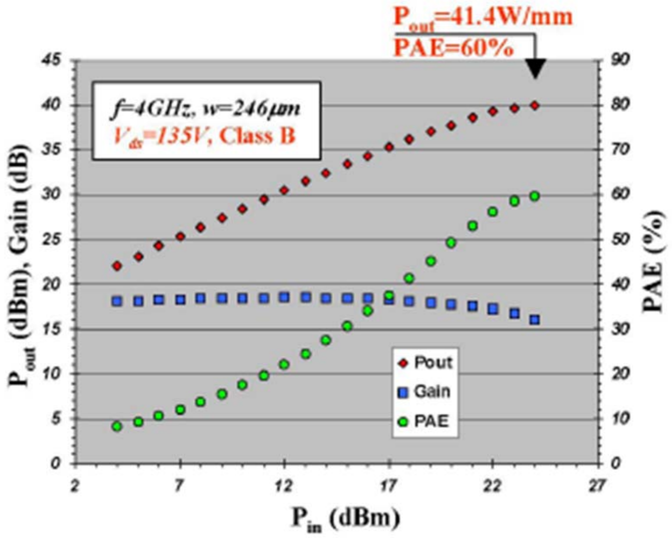
AlGaN/GaN system uniqueness:

- Strong polarization “doping” → high current operation
- High breakdown voltage → high voltage operation
- High saturation velocity → high frequency operation

Breakthrough high-f PAs

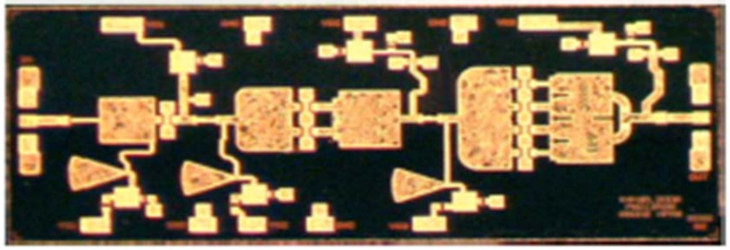
Breakthrough RF Power in GaN HEMTs





P_{out} > 40 W/mm, over 10X GaAs!

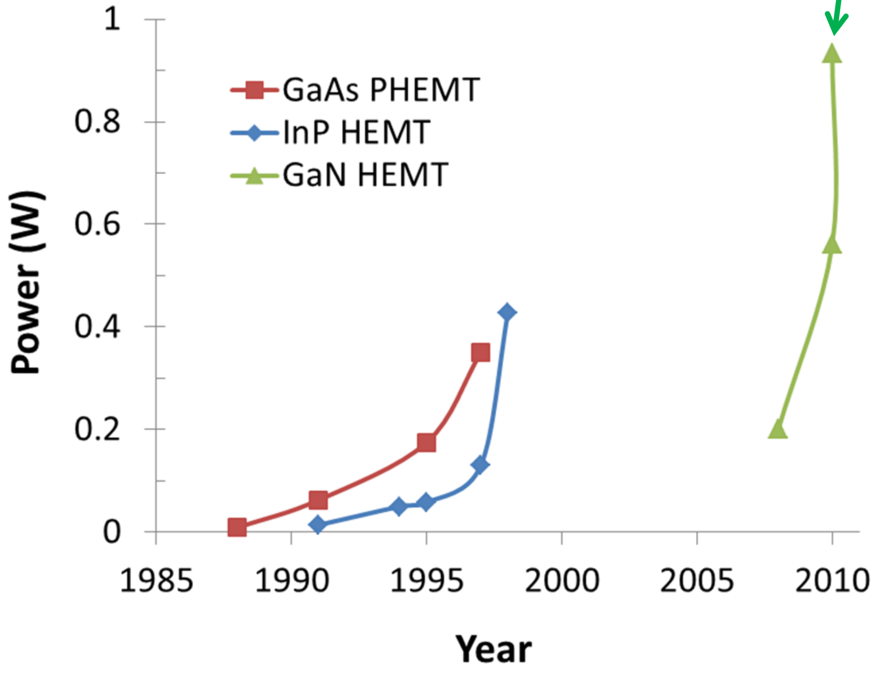
Wu, DRC 2006



Micovic, MTT-S 2010

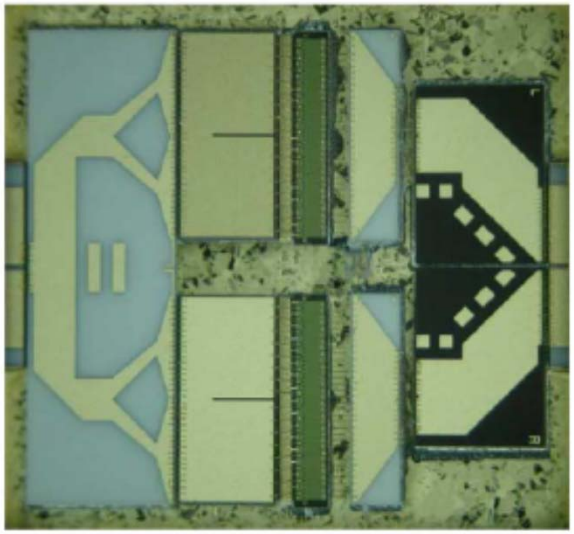
Micovic, Cornell Conf 2010

94-95 GHz MMIC PAs:

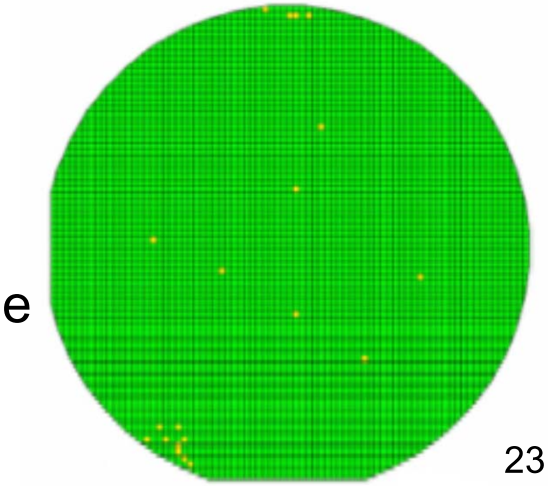


GaN HEMT in the field

Counter-IED Systems (CREW)



200 W GaN HEMT for cellular base station
Kawano, APMC 2005

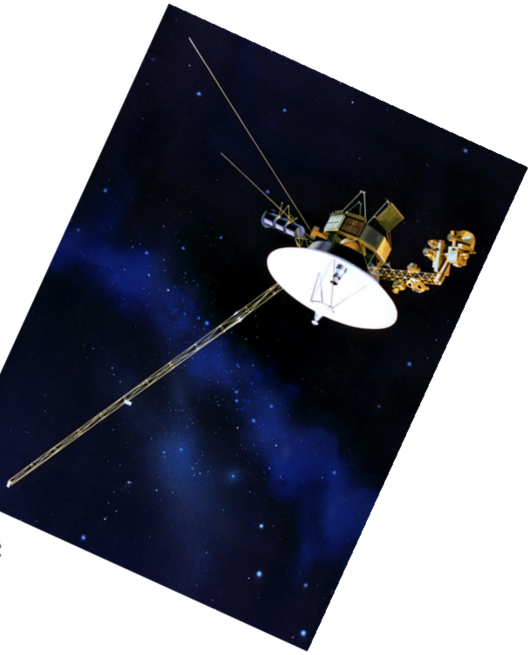


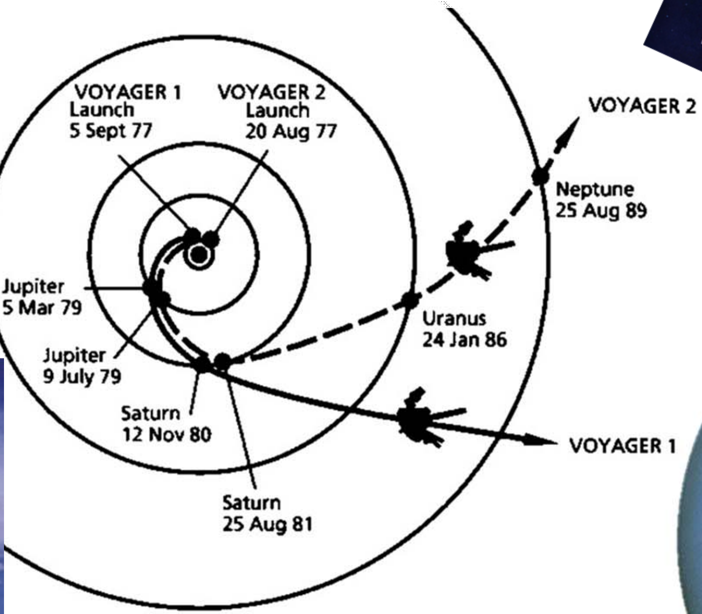
100 mm GaN-on-SiC volume manufacturing
Palmour, MTT-S 2010

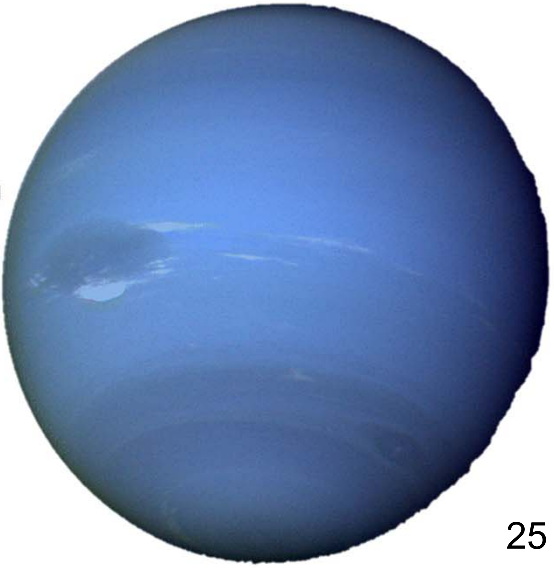
Modulation-doped structures in physics

Cryogenic HEMTs in radioastronomy

- 1977: launch of Voyager 1 & 2, in mission to four planets
- 1987: AlGaAs/GaAs HEMT amplifiers delivered by GE to Very Large Array (Socorro, NM)
- 1989: Voyager 2 Neptune encounter



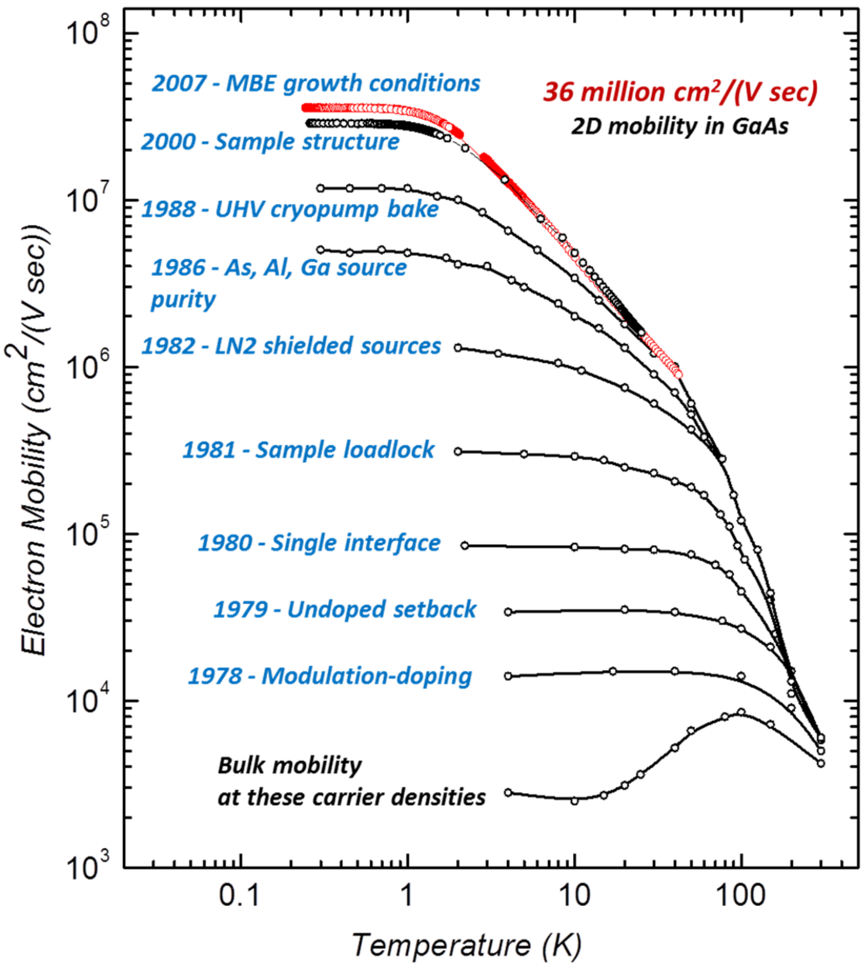




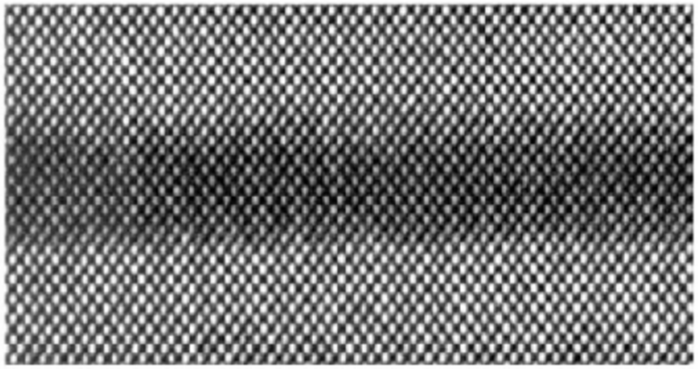
Courtesy of Phillip Smith (BAE Systems)

Modulation-doped structures in physics

AlGaAs/GaAs heterostructure: perhaps *the most perfect crystalline interfacial system ever fabricated*



Courtesy of Loren Pfeiffer (Princeton)



μ_e=3.6x10^7 cm^2/V.s at 0.36 K

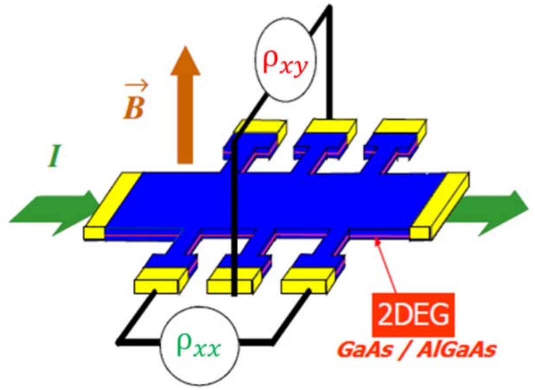
(n_s=3x10^{11} cm^{-2})

Umansky, JCG 2009

μ ↑: less disorder

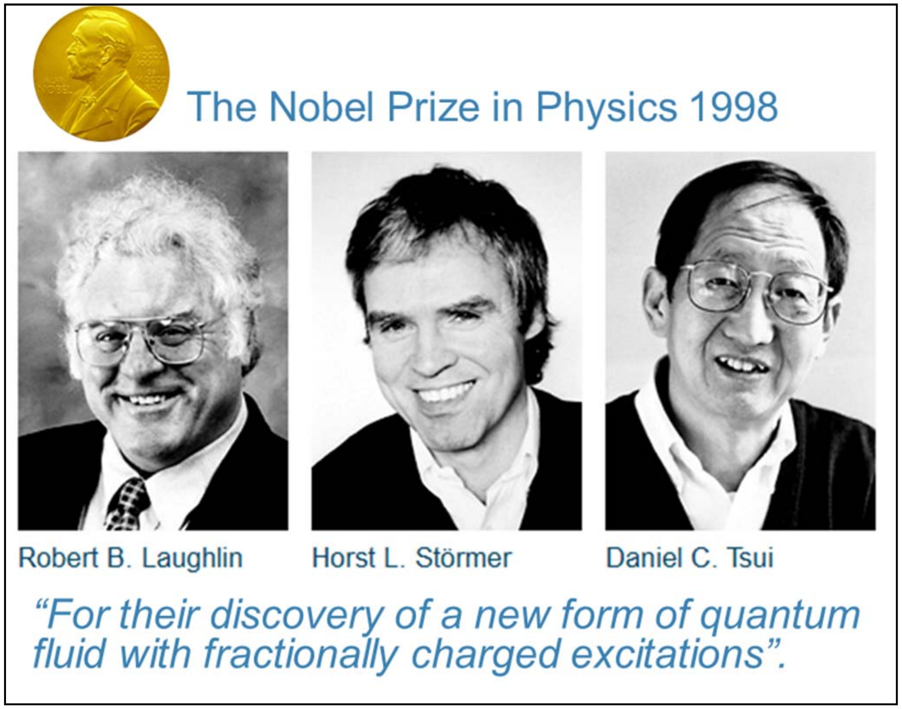
→ new physics!

Fractional quantum-Hall effect



$$\rho_{xy} = \frac{h}{ie^2}$$

index



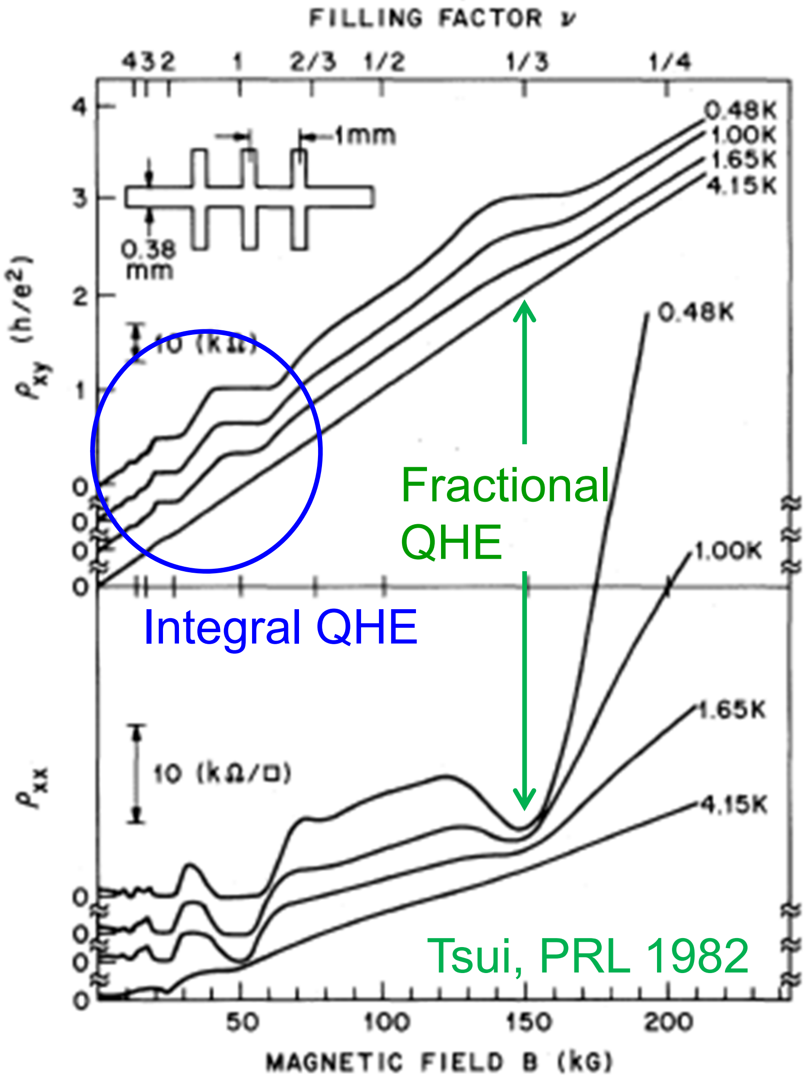
The Nobel Prize in Physics 1998

Robert B. Laughlin

Horst L. Störmer

Daniel C. Tsui

"For their discovery of a new form of quantum fluid with fractionally charged excitations".



Fractional QHE

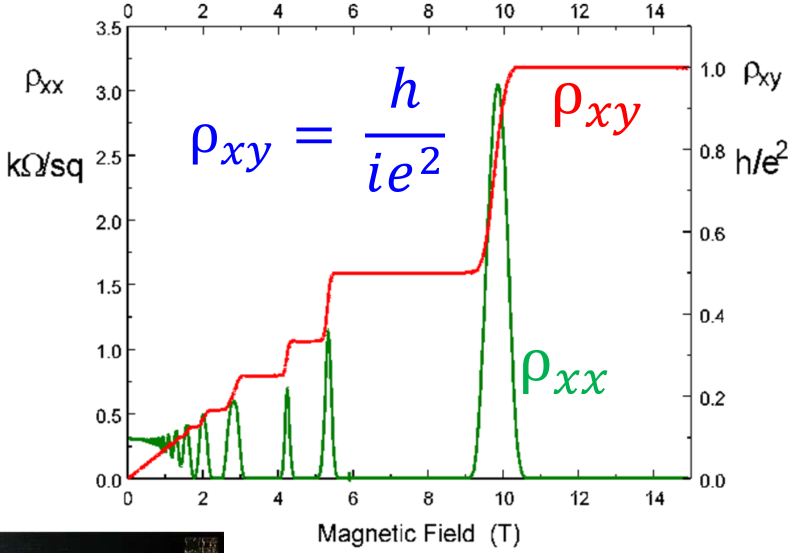
Integral QHE

Tsui, PRL 1982

Discovered in sample with μ_e=9x10^4 cm^2/V.s

New international standard for Ohm: AlGaAs/GaAs quantum-Hall bar array

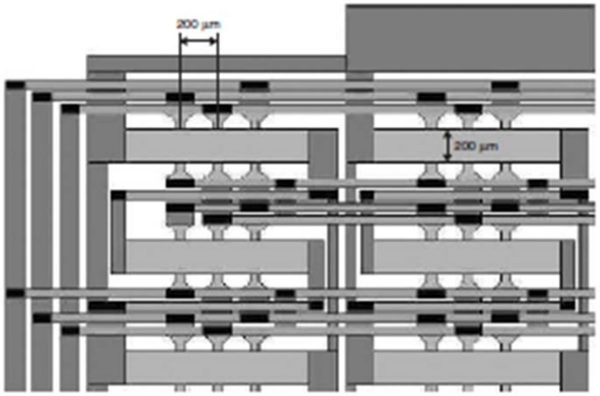
Hall plateaus in Integral QHE determined by fundamental constants
→ use Hall resistance to define Ohm

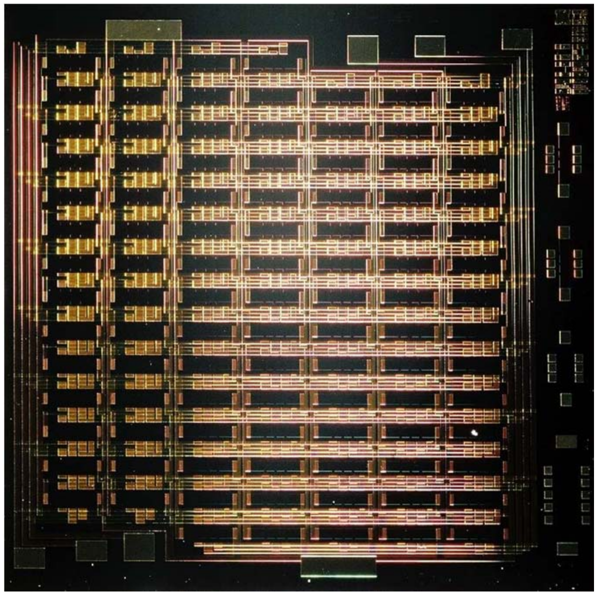


$$\rho_{xy} = \frac{h}{ie^2}$$

AlGaAs/GaAs quantum-Hall bar array:

- adopted in 1990 as standard for Ohm
- precision: few parts in 10^9!
- 100 Hall bars
- μ_e~6×10^5 cm^2/V.s



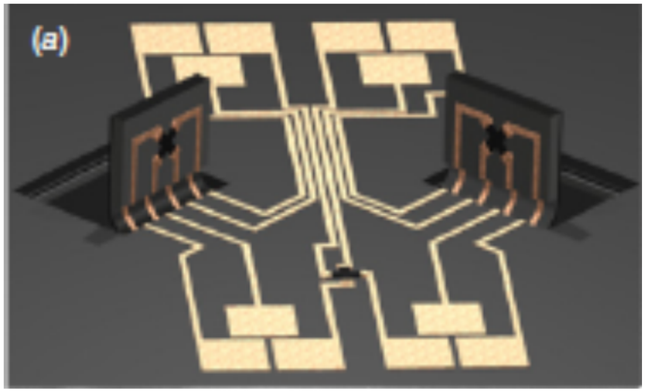


Previous Ohm standard (manganin wire):

Courtesy of Wilfrid Poirier (Laboratoire National de Métrologie et d'Essais)

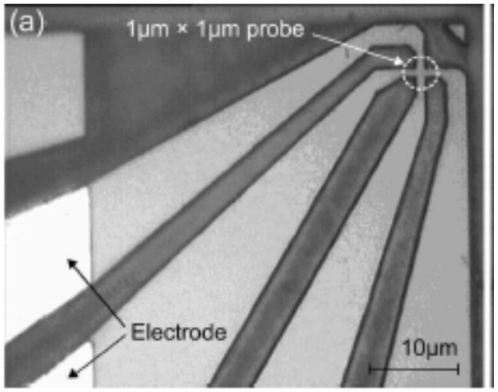
Future prospects

New sensors



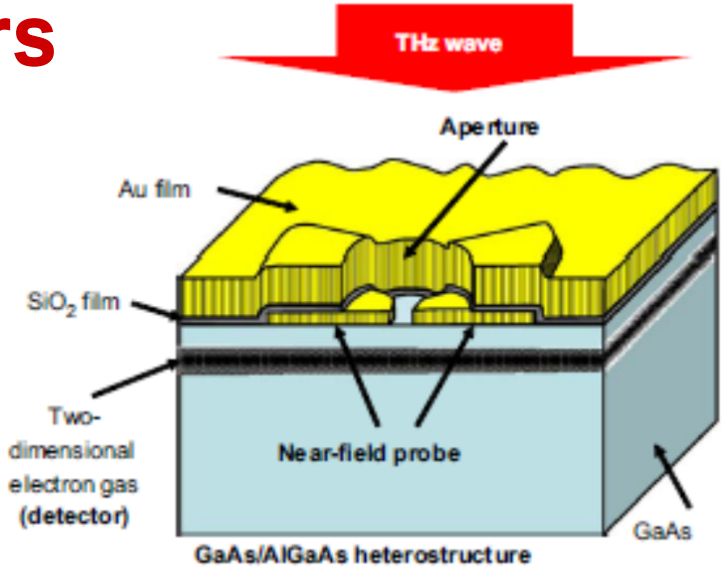
AlGaAs/GaAs 3-axis Hall sensors

Todaro JMM 2010



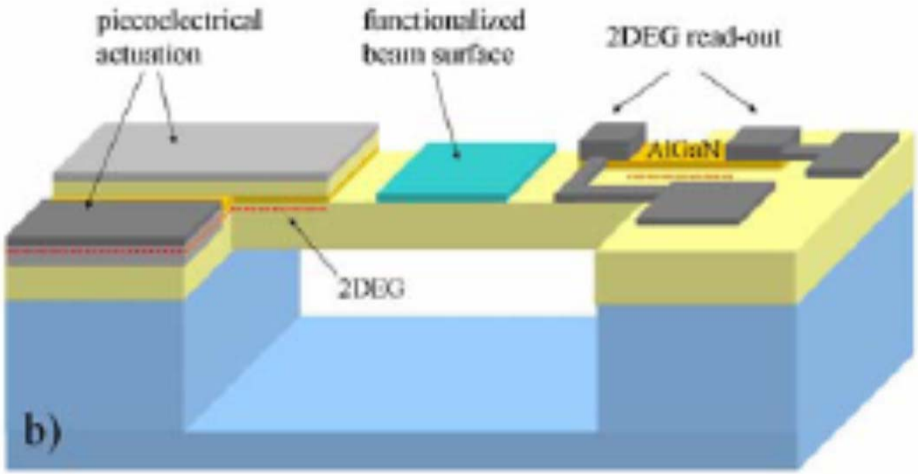
InAlSb/InAsSb Micro-Hall sensors

Bando, JAP 2009



AlGaAs/GaAs THz devices

Kawano, Phys E 2010

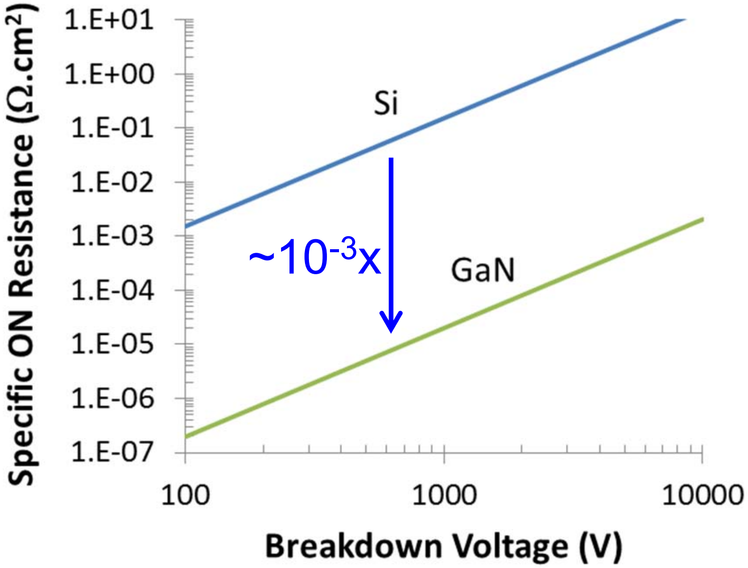


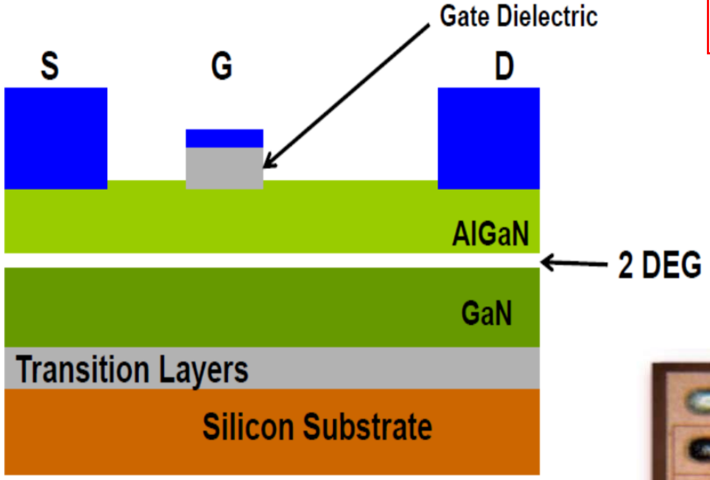
AlGaN/GaN Bio sensors

Niebelschutz, PSSc 2008

GaN power electronics

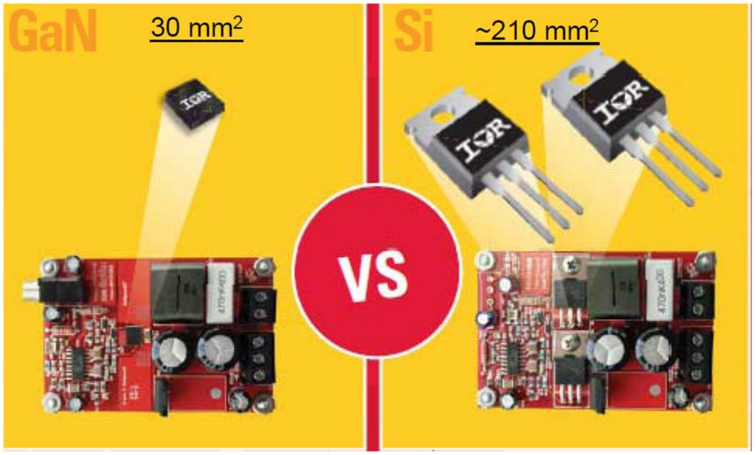
$26B market in 2008





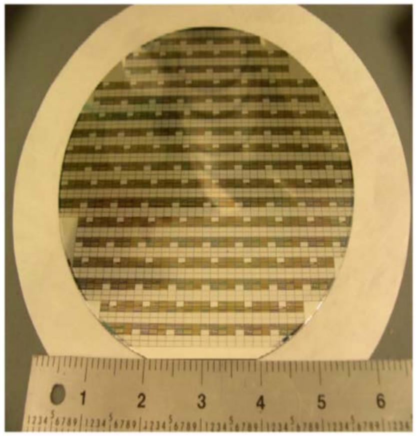
Briere, APEC 2011

GaN enables size shrink:



+

Si-like economics:

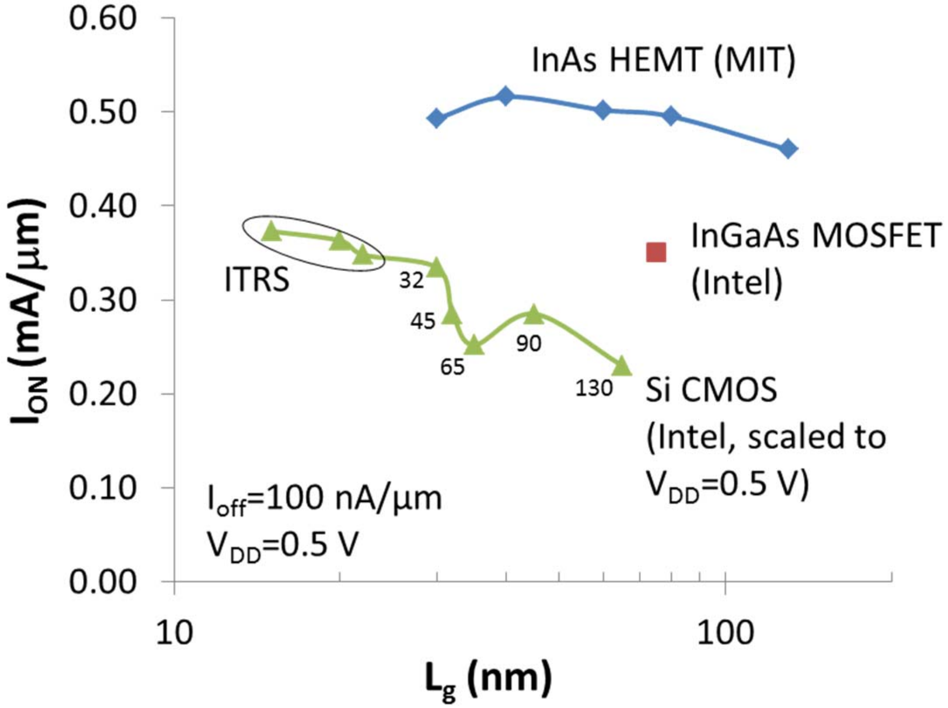


=

2-3x performance/cost advantage over Si

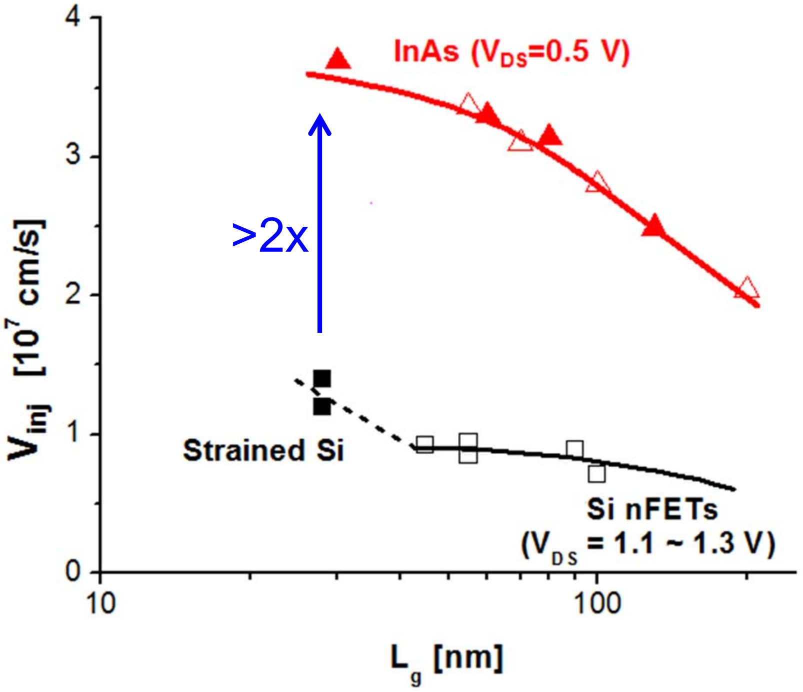
III-V CMOS

III-V FETs exceed logic performance of Si at 0.5 V

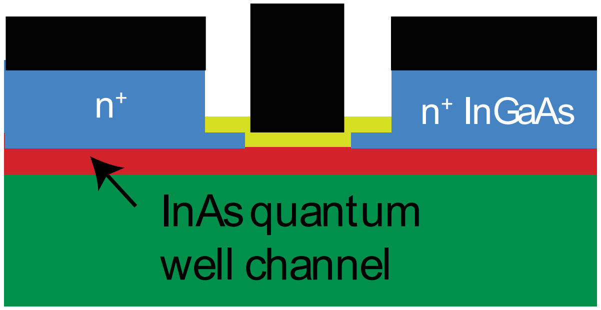


del Alamo, IPRM 2011

v_{inj} in InGaAs >2x higher than Si at half the voltage



Kim, IEDM 2009



$110B market in 2010!

Epilogue:

Kroemer’s Lemma of New Technology

“The principal applications of any sufficiently new and innovative technology have always been – and will continue to be – applications *created* by that technology.”

Kroemer, Rev Mod Phys 2000

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