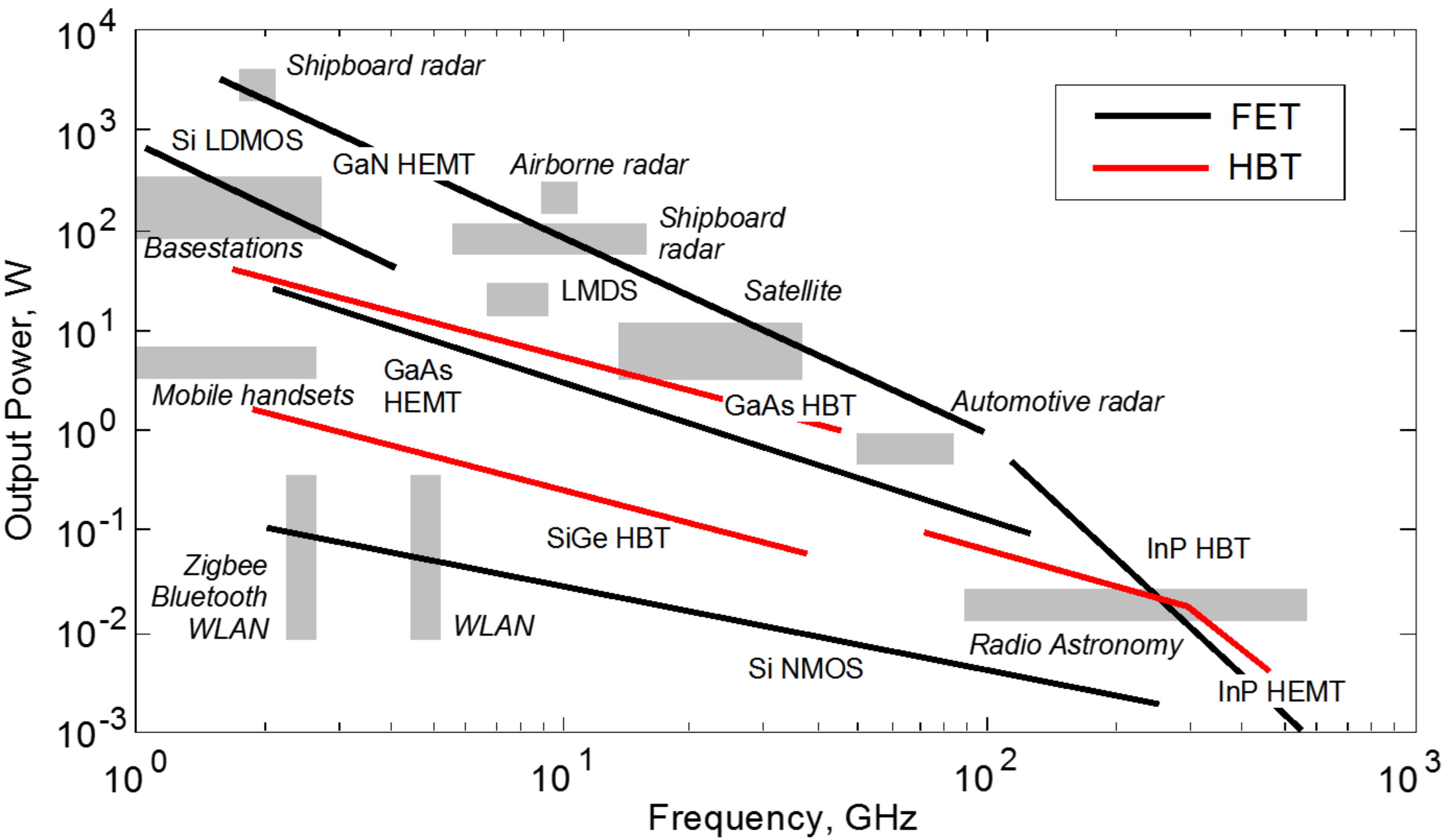
Active RF and microwave components

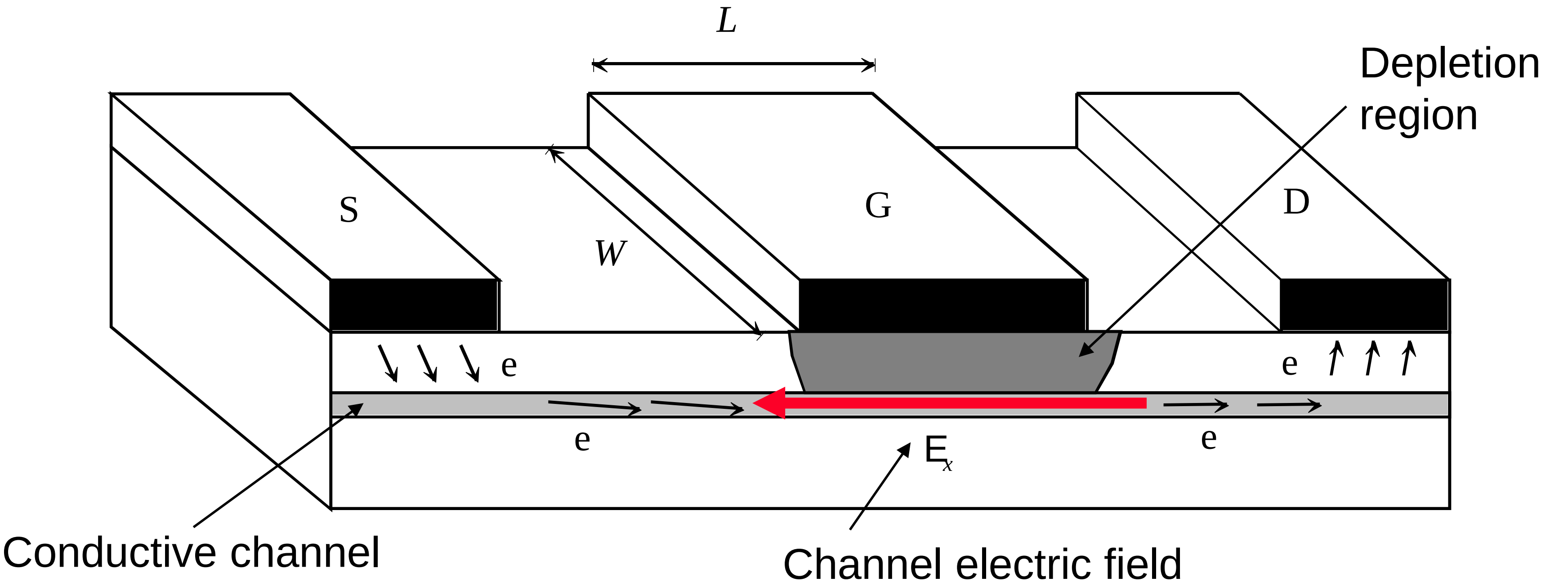
Microwave Electronics
Giovanni Ghione, Marco Pirola
Politecnico di Torino, DET

RF devices spectrum and applications

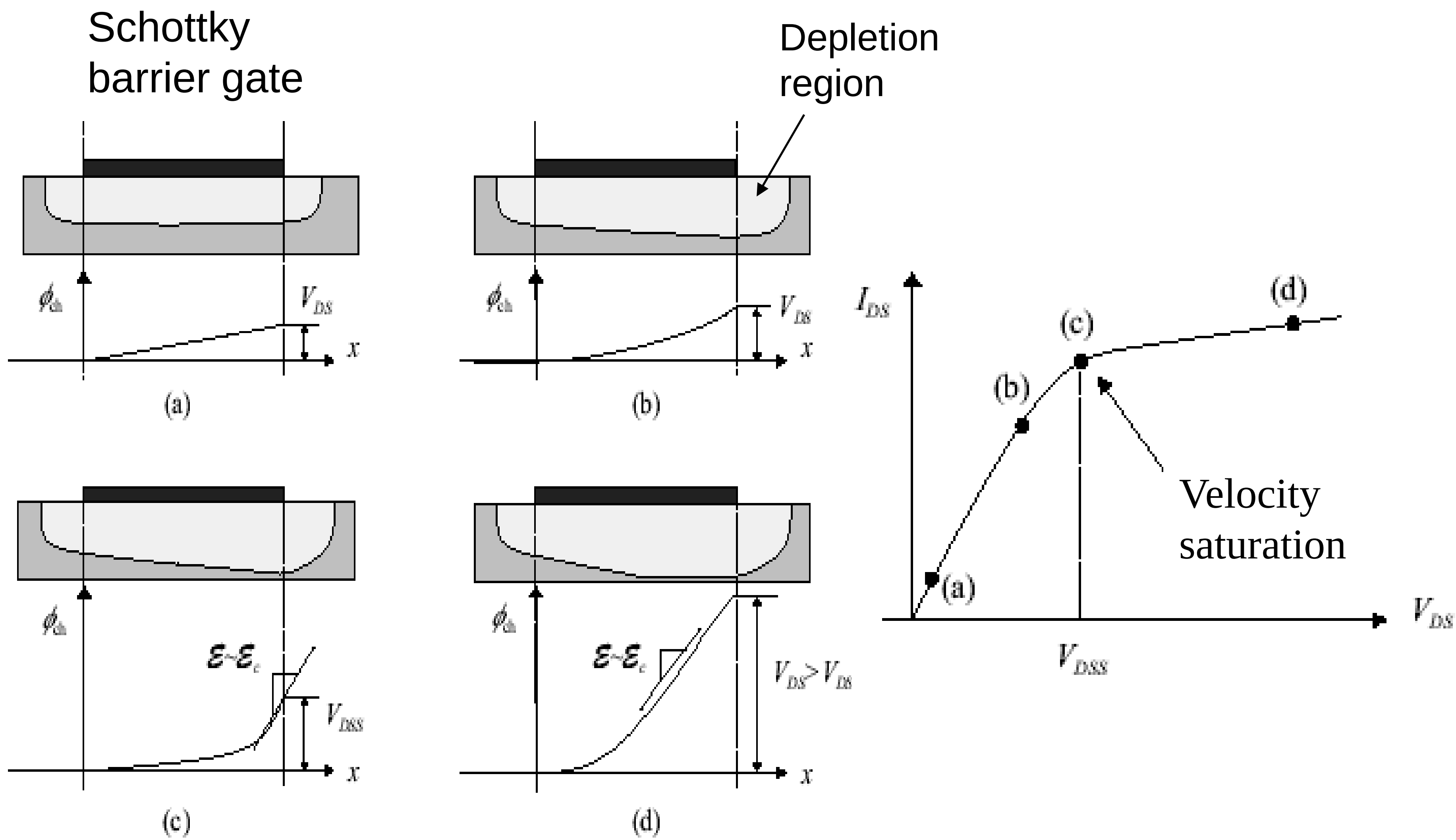


The Compound Semiconductor FET

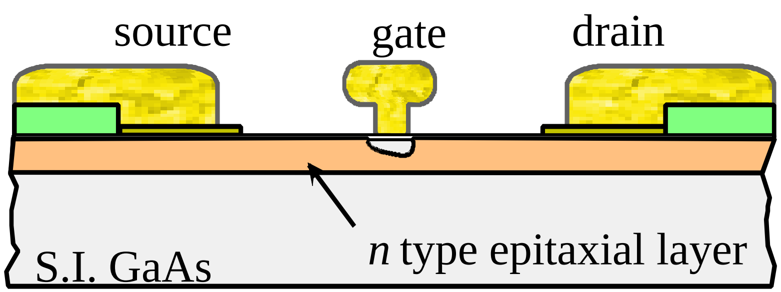
- The microwave FET structure and operation is conventional; difference between devices depends on the way the channel is implemented
- Evolution: MESFET → HEMT → PHEMT (MHEMT)
- Material evolution: GaAs → AlGaAs → InP based alloys



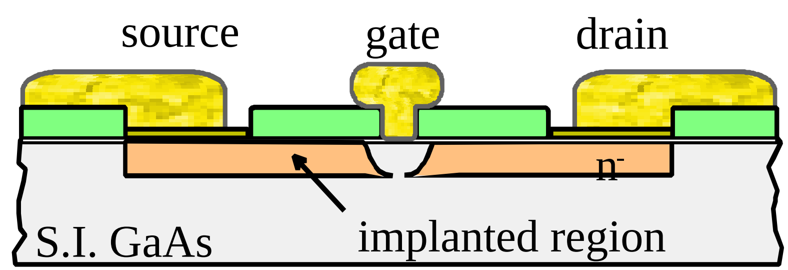
MESFET operation



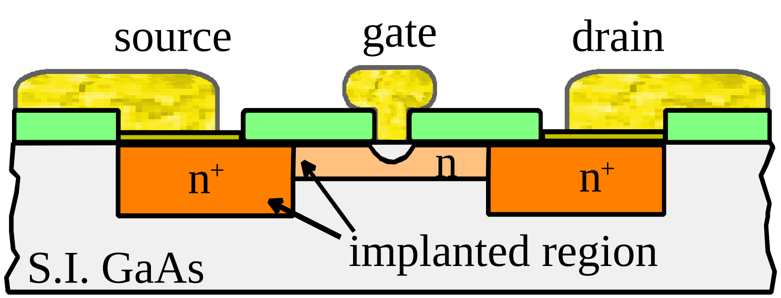
MESFET examples



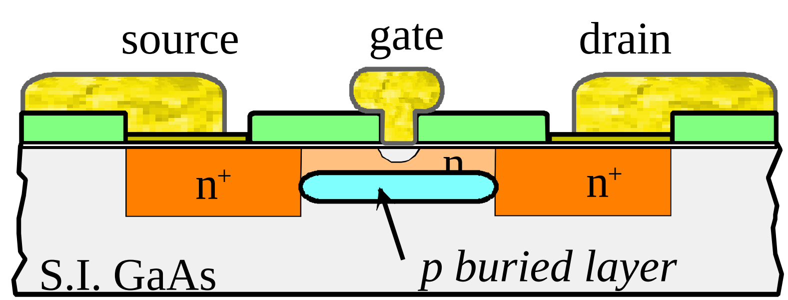
EPITAXIAL MESFET



IMPLANTED ENHANCEMENT MESFET

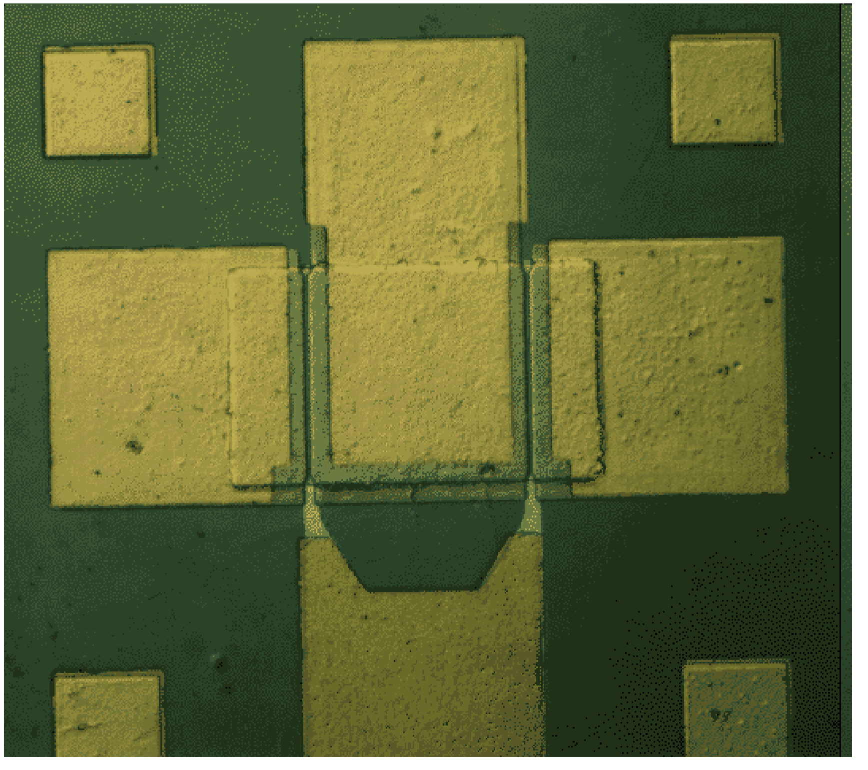


IMPLANTED DEPLETION MESFET



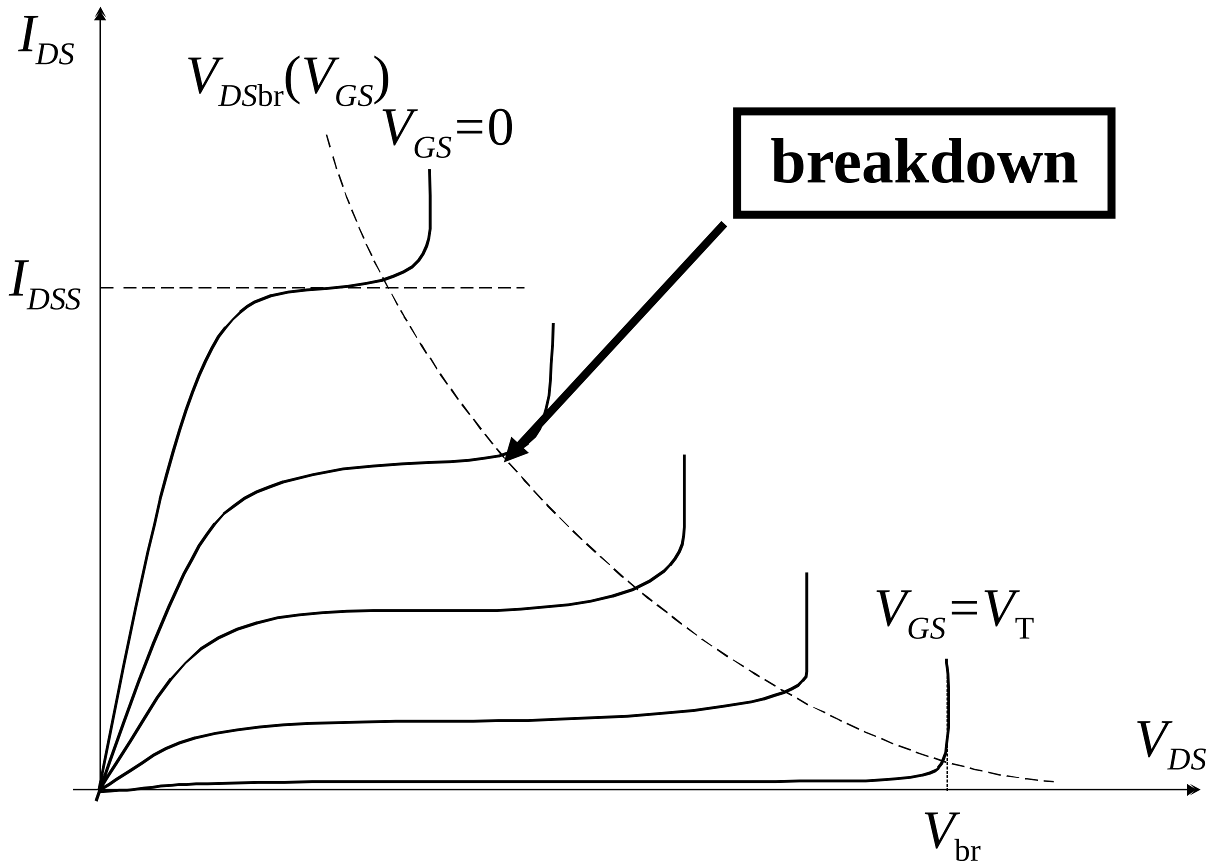
IMPLANTED MESFET
WITH P-BURIED LAYER

Early MESFET layout



CISE (MI) MESFET – 1983
from MONOMIC project

MESFET DC characteristics



Compound semiconductor alloys

- Semiconductor alloys have "average" properties (*energy gap, lattice constant*) with respect to components, can be grown on a ***lattice-matched*** (or almost LM) substrate to emit specific wavelengths (optoelectronics) or to carry out some *energy band engineering* (see later) useful to specific devices
- Examples:

$$\left(\mathrm{GaAs}\right)_{1\text{-x}} + \left(\mathrm{AlAs}\right)_{\mathrm{x}} = \mathrm{Al_xGa_{1\text{-}x}As}$$

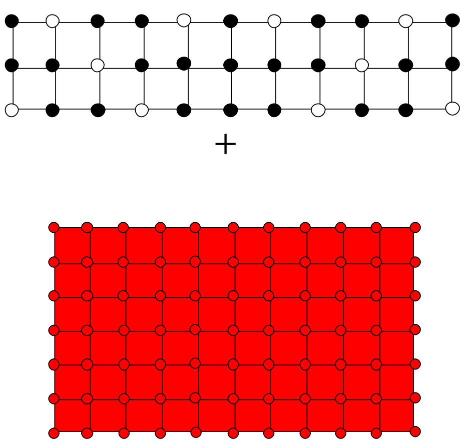
$$\left(\mathrm{GaAs}\right)_{\alpha} + \left(\mathrm{InP}\right)_{\beta} + \left(\mathrm{InAs}\right)_{\gamma} + \left(\mathrm{GaP}\right)_{\delta} \overset{(\alpha+\beta+\gamma+\delta=1)}{=}$$

$$= \mathrm{In}_{\beta+\gamma}\mathrm{Ga}_{\alpha+\delta}\mathrm{As}_{\alpha+\gamma}\mathrm{P}_{\beta+\delta} = \mathrm{In_xGa_{1\text{-}x}As_yP_{1\text{-}y}}$$

Lattice-Matched and Strained (Pseudomorphic) Epitaxy

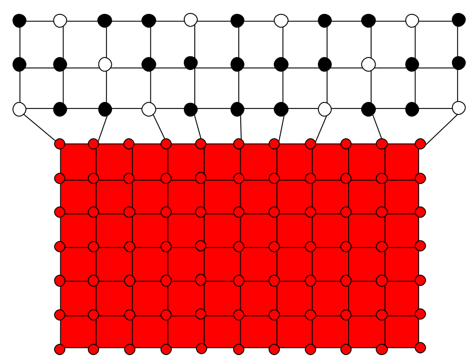
- Lattice matching usually essential, a slight amount of mismatching can be beneficial in opto & electron devices

Epitaxial layer



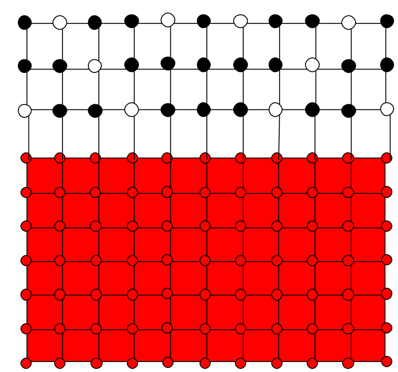
Substrate

Epitaxial, non pseudomorphic



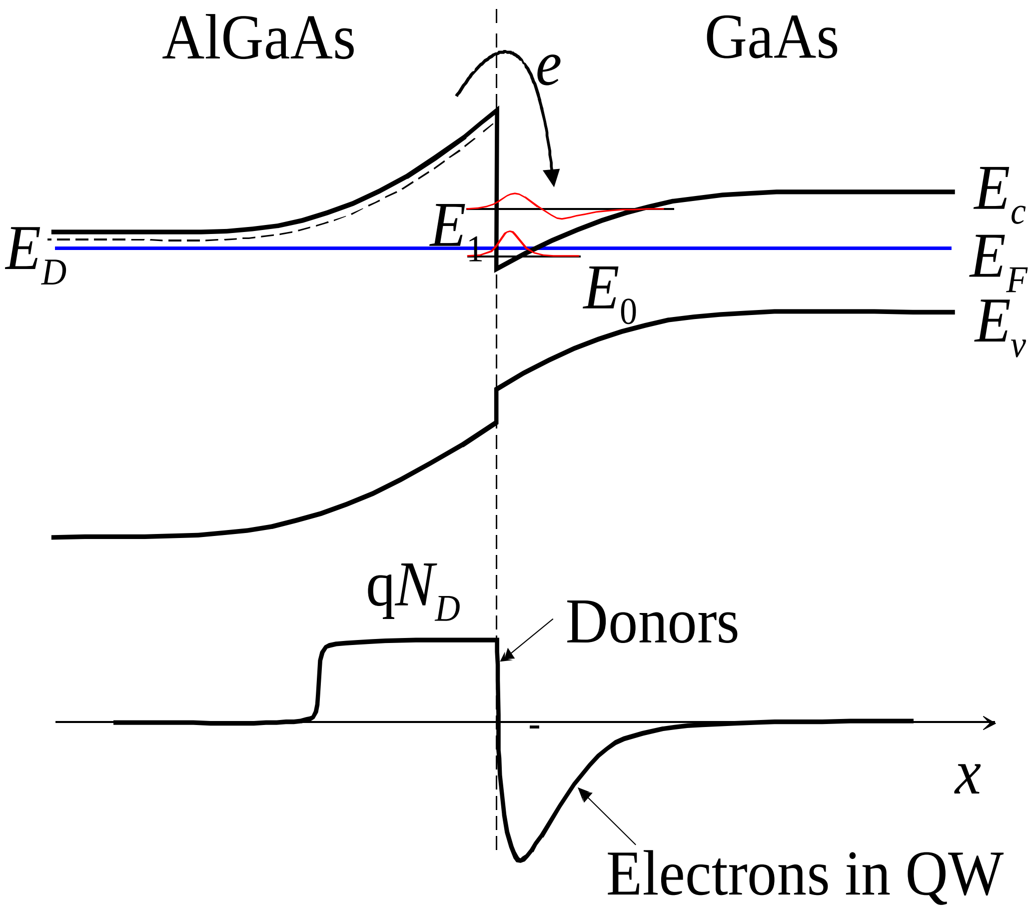
Substrate

Epitaxial, strained or pseudomorphic



Substrate

Modulation doped heterostructure



- Heterostructure between a doped widegap material and a semi-insulating narrowgap material
- An interface quantum well is created were electron move from the doped region creating a 2-dimensional electron gas (2DEG)

HEMT: the 2DEG exploited as the FET channel

- The carrier density (sheet density) n_s in the 2DEG is modulated by the gate voltage (as in MOS devices)

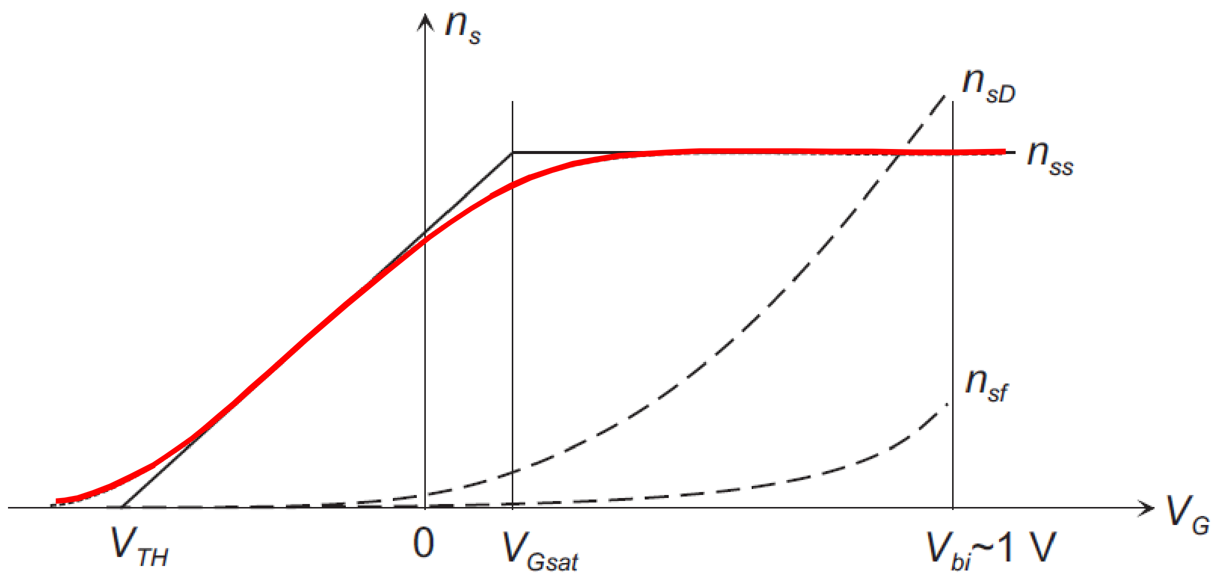
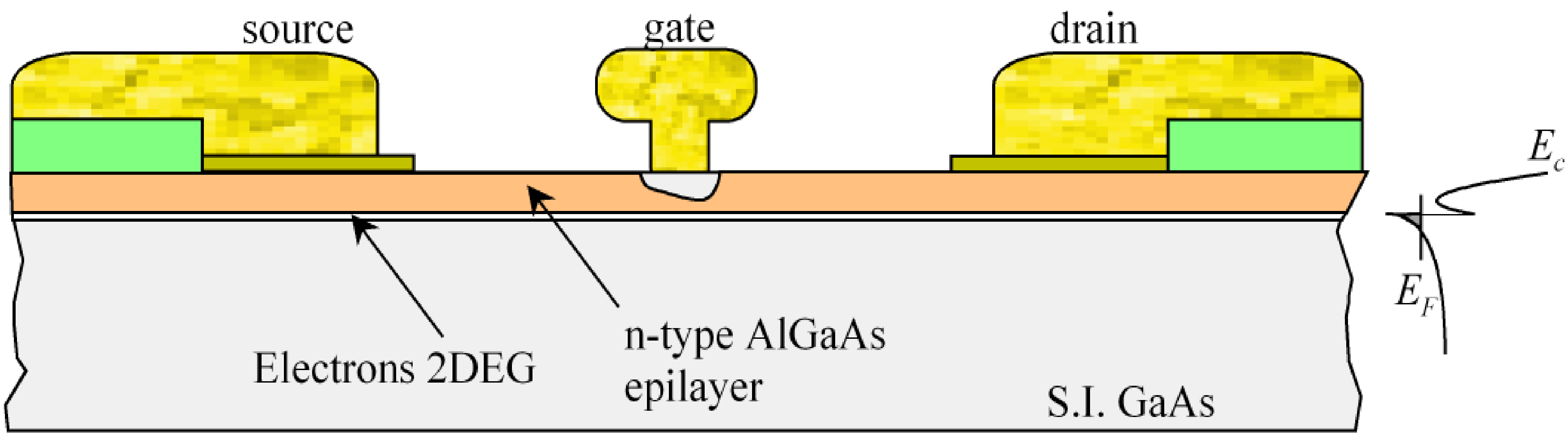


Figure 5.37 Behaviour of sheet carrier density n_s for a PHEMT as a function of the gate bias. V_{TH} is the threshold voltage, V_{Gsat} is the gate voltage at which the sheet carrier density saturates at n_{ss}, V_{bi} is the Schottky gate barrier built-in voltage. The sheet carrier densities n_{sD} and n_{sf} refer to the donor trapped carriers and free carriers in the supply layer, respectively.

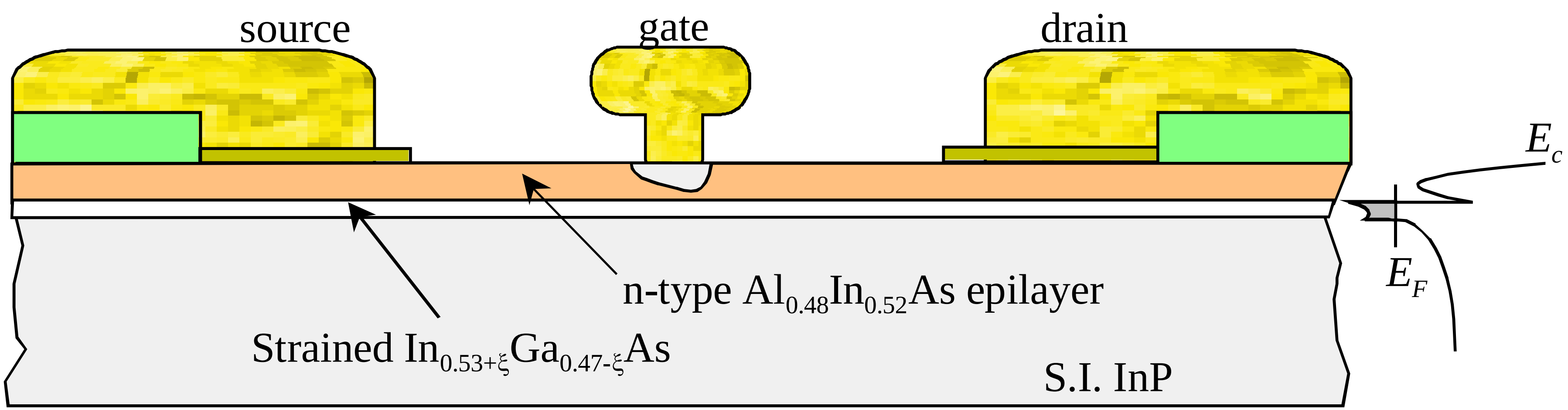
The conventional HEMT

- Triangular QW made with GaAs-AlGaAs system
- Good low-noise to medium power device, limited by reduced conduction band discontinuity
- High-electron-mobility concept only at low temperature



The QW Lattice-Matched or Pseudomorphic HEMT (PHEMT)

- Increased transconductance obtained through square QW
- Strained layers permit to increase the conduction band discontinuity
- Best results with InP-based devices, GaAs based more important for the applications

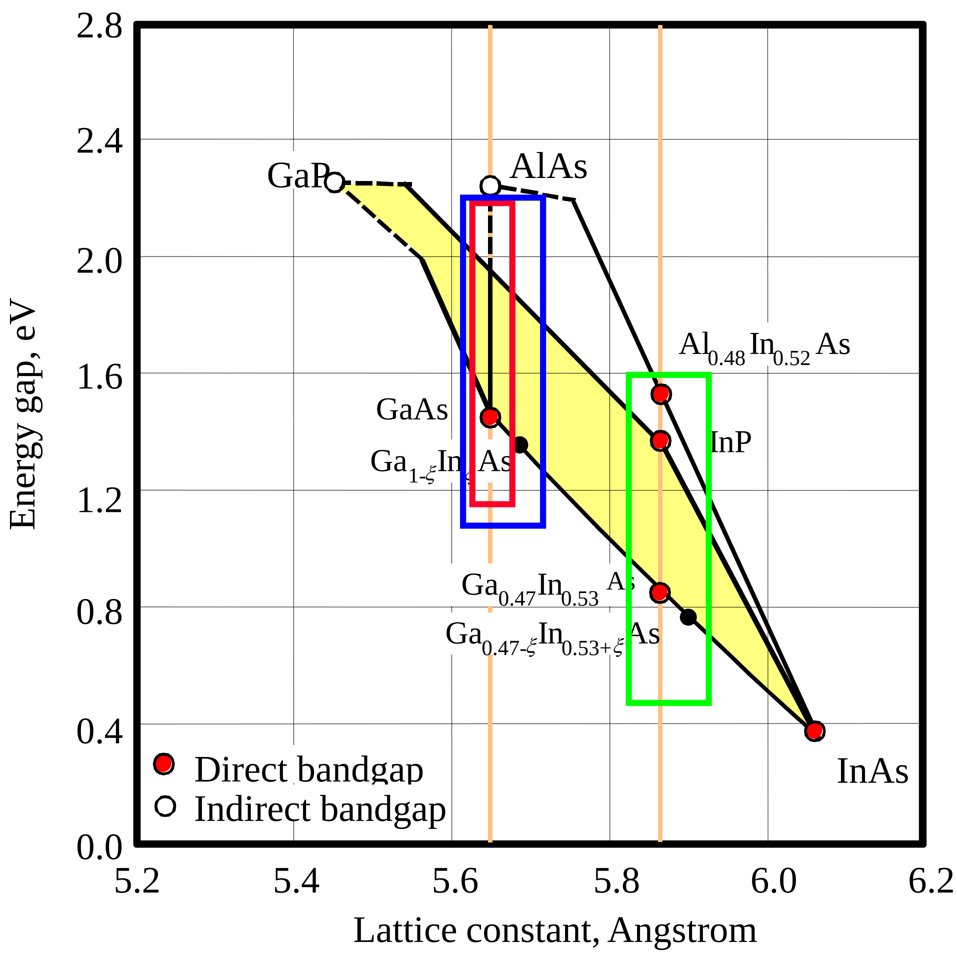


GaAs and InP based (P)HEMTs

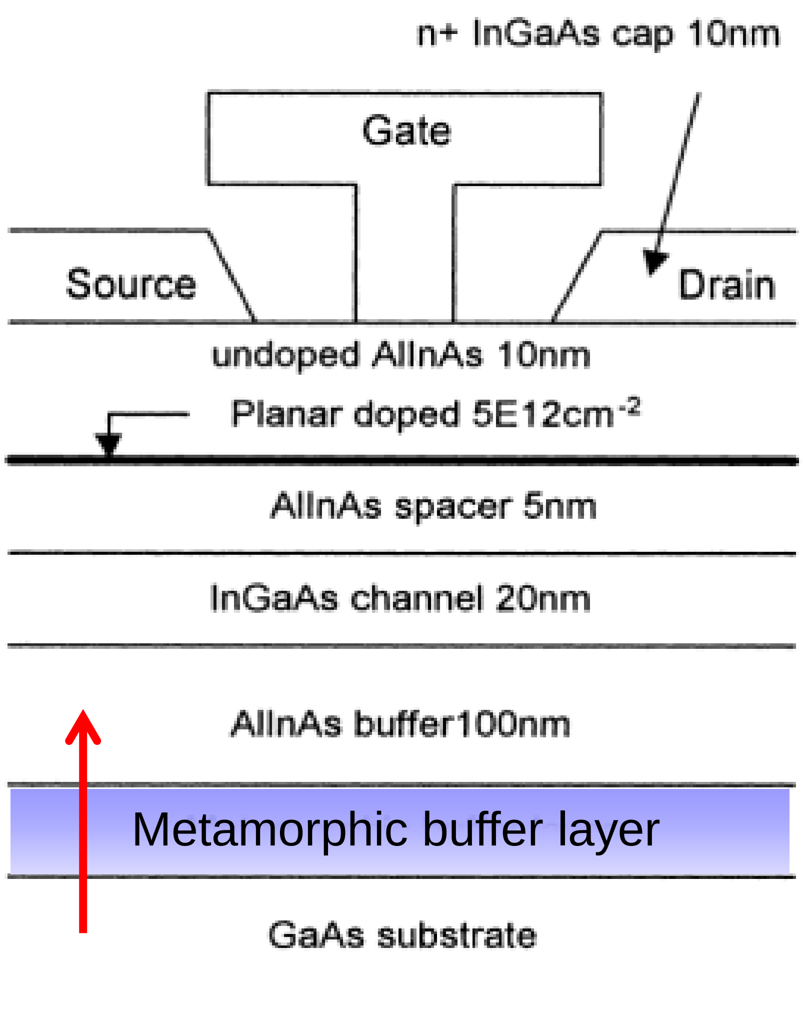
- Conventional HEMT: GaAs substrate, AlGaAs supply layer

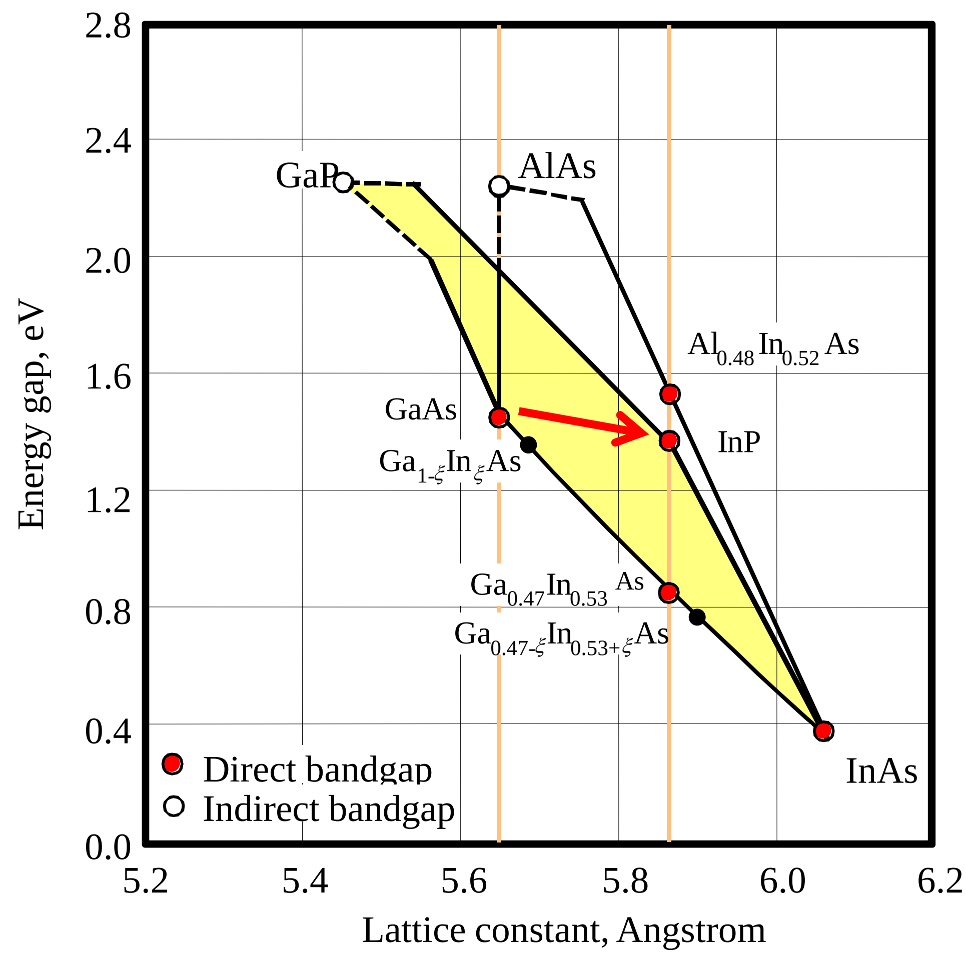
- GaAs-based PHEMT: GaAs substrate, InGaAs (PM) channel, AlGaAs supply layer

- LMHEMT and PHEMT on InP: InP substrate, InGaAs (LM or PM) channel, InAlAs supply layer



The Metamorphic HEMT (MHEMT)





mHEMT → Metamorphic HEMT → InP like
on GaAs through variable composition buffer

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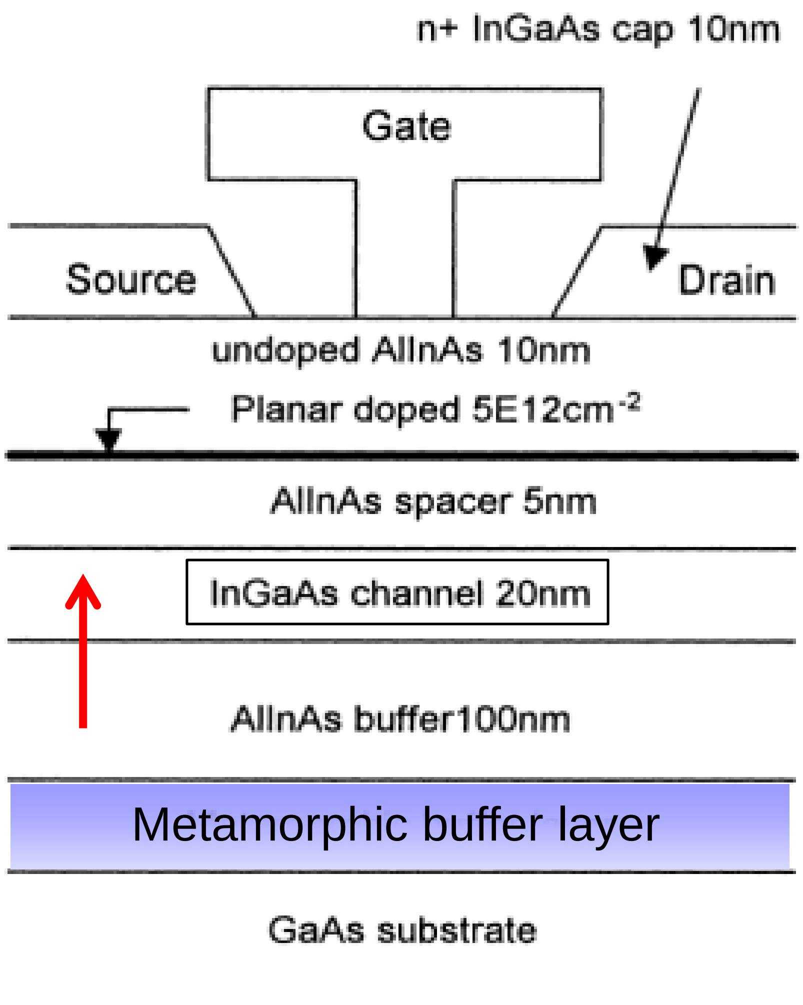

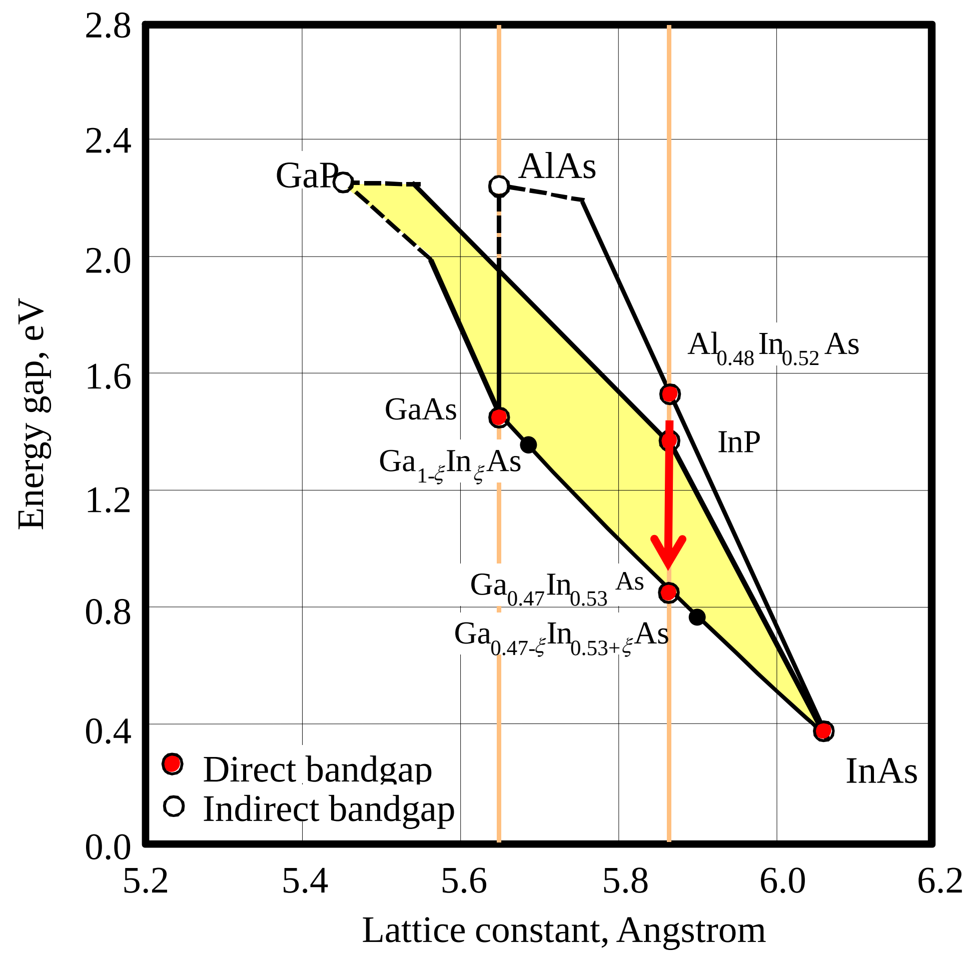

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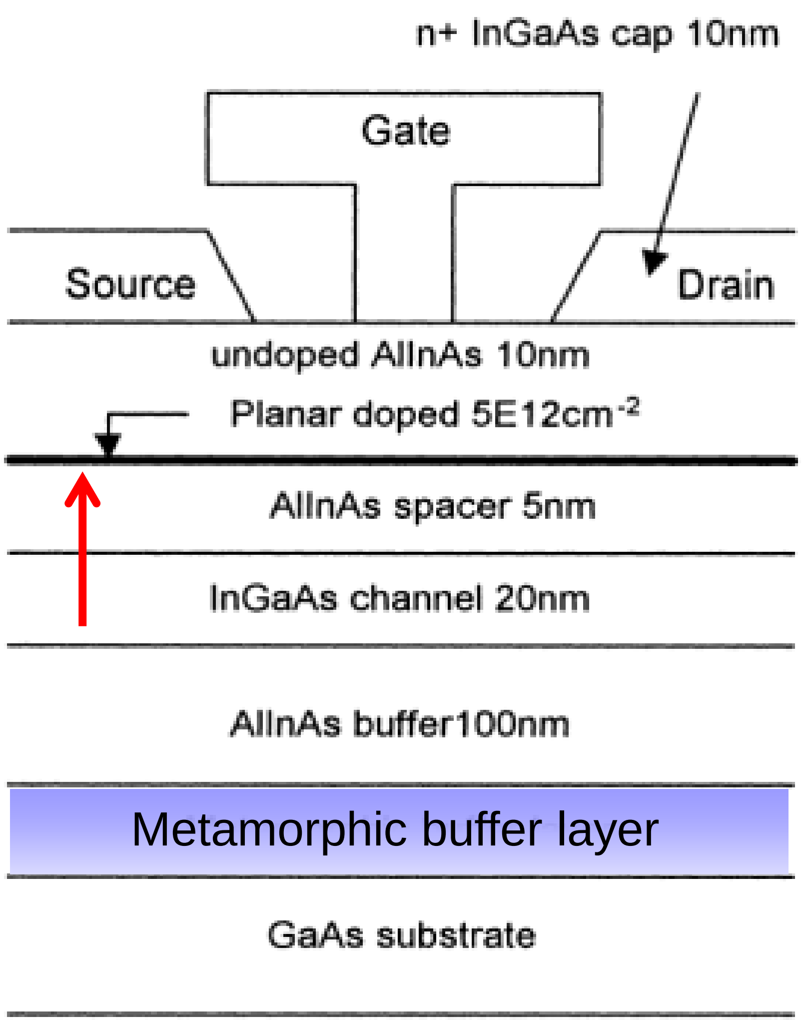

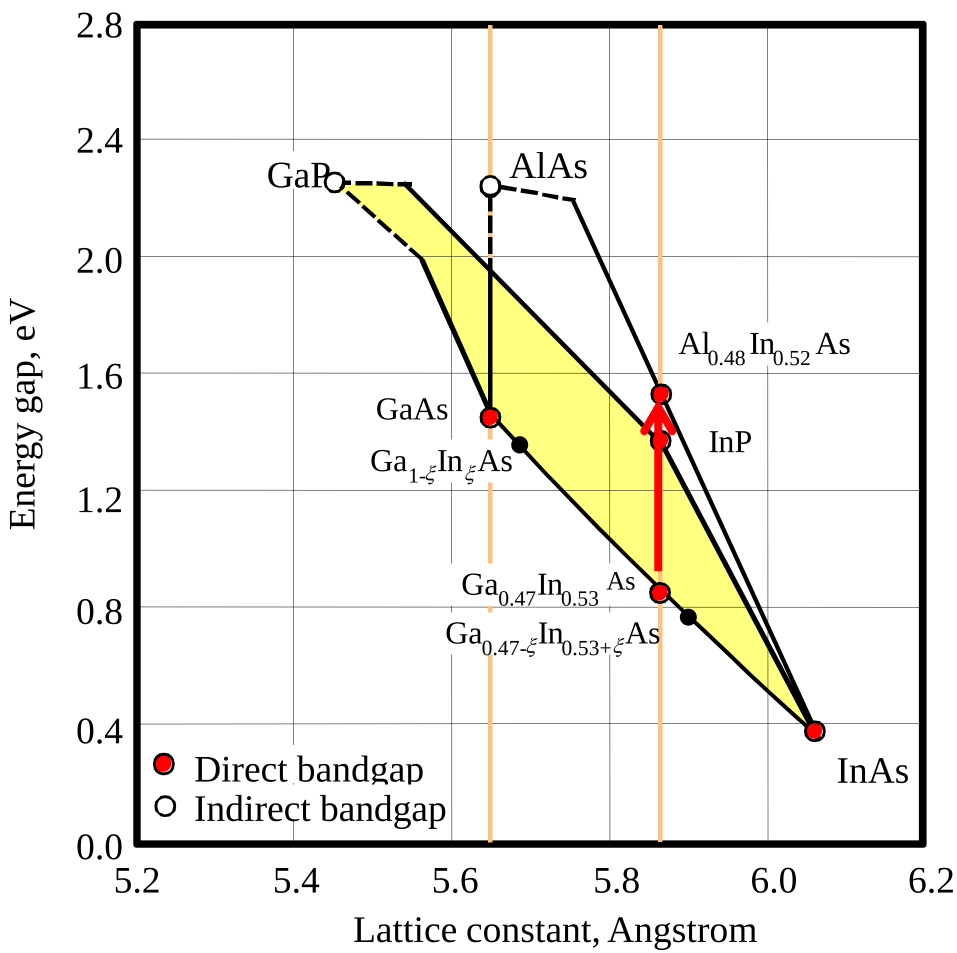

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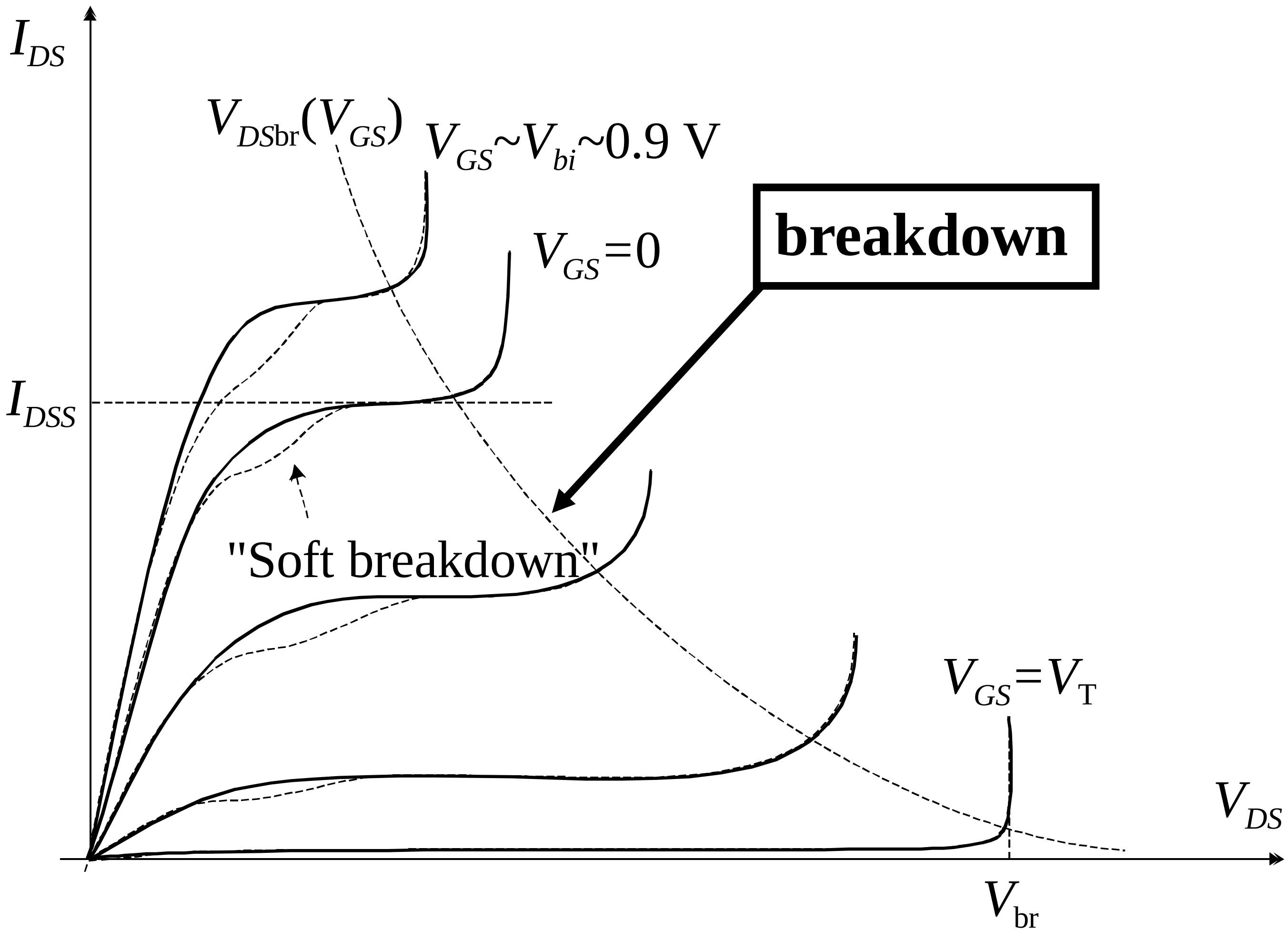
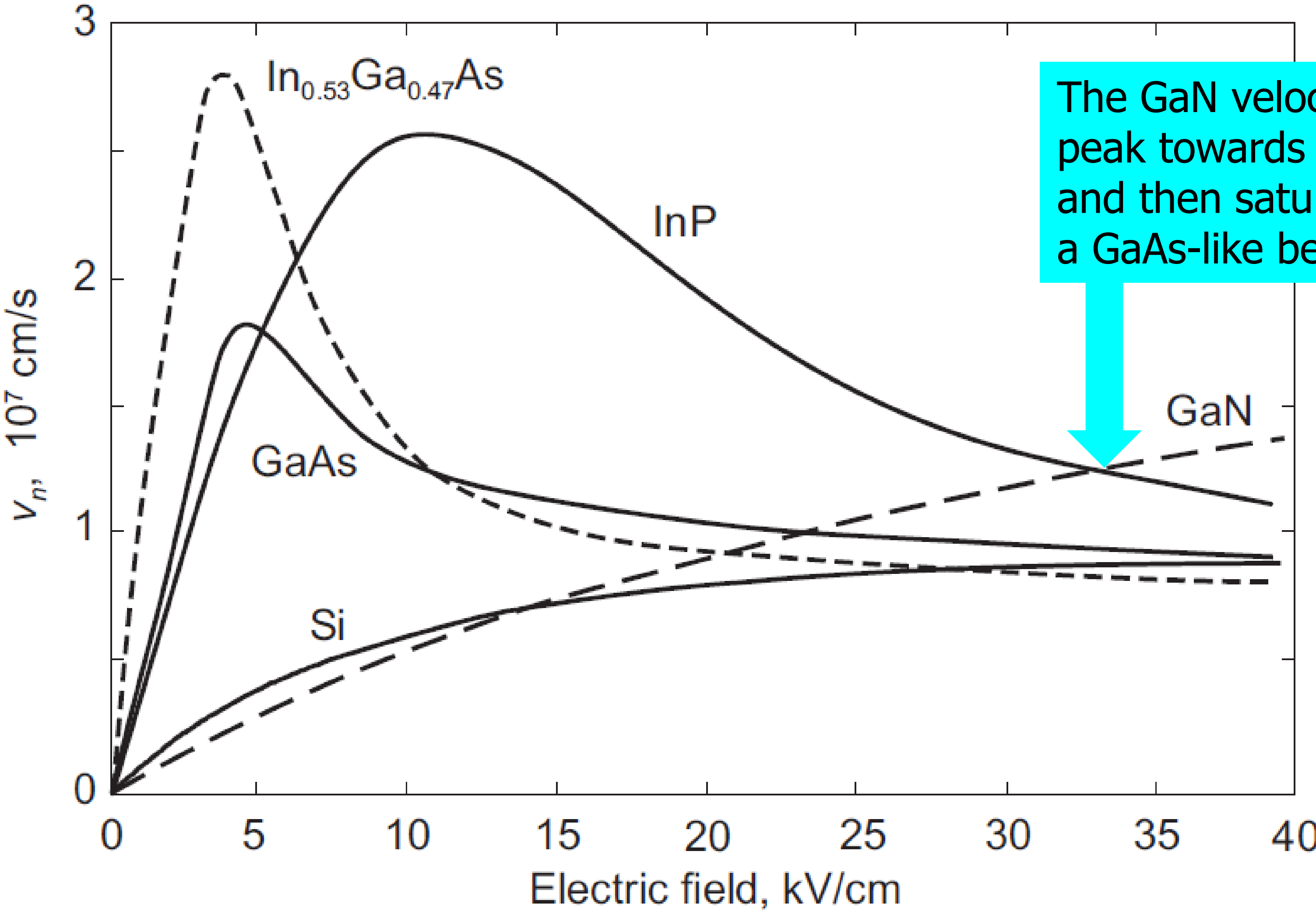
(P)HEMT DC characteristics



Widegap materials: GaN, SiC

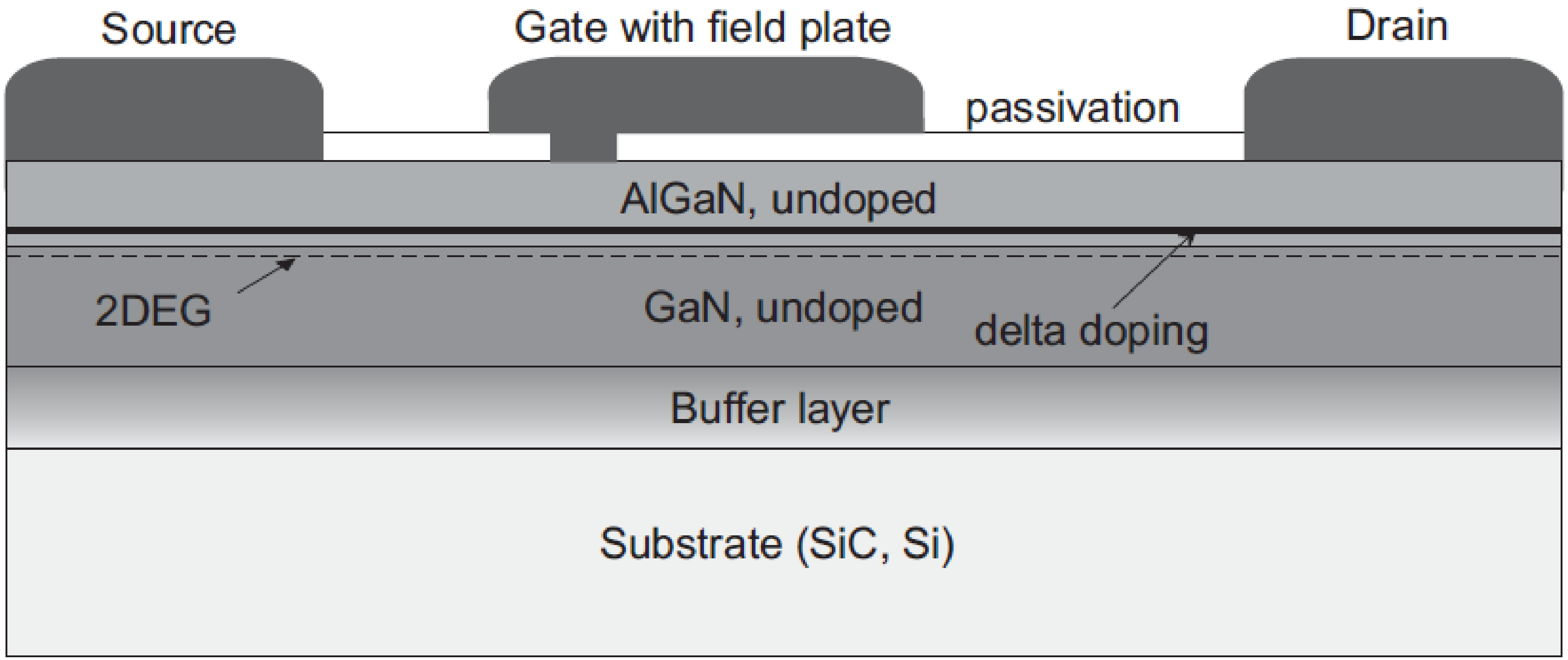
Material property		Device FOM improved	System advantage
High breakdown field	High voltage	Power density Efficiency Output impedance	Smaller Die count per system Lower energy usage
High thermal conductivity, wide bandgap	High T	Small die size More power per die	Smaller/cheaper package Relaxed system cooling
High electron velociry	High frequency	High fT and fmax	Higher system frequency Power density

More on velocity-field curve



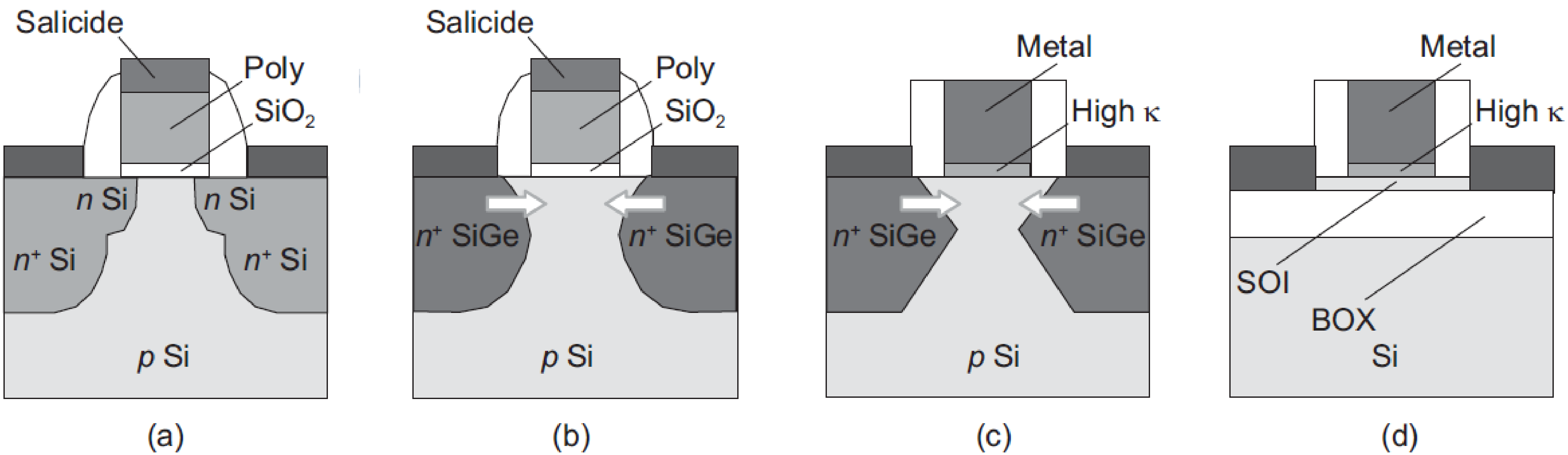
The GaN velocity has a peak towards 200 kV/cm and then saturates with a GaAs-like behaviour

AlGaN/GaN HEMT



- Power GaN devices can reach power densities (CW) in excess of 10 W/mm at microwave frequencies, i.e. ~10 x other III-V technologies

MOSFET downsizing and evolution



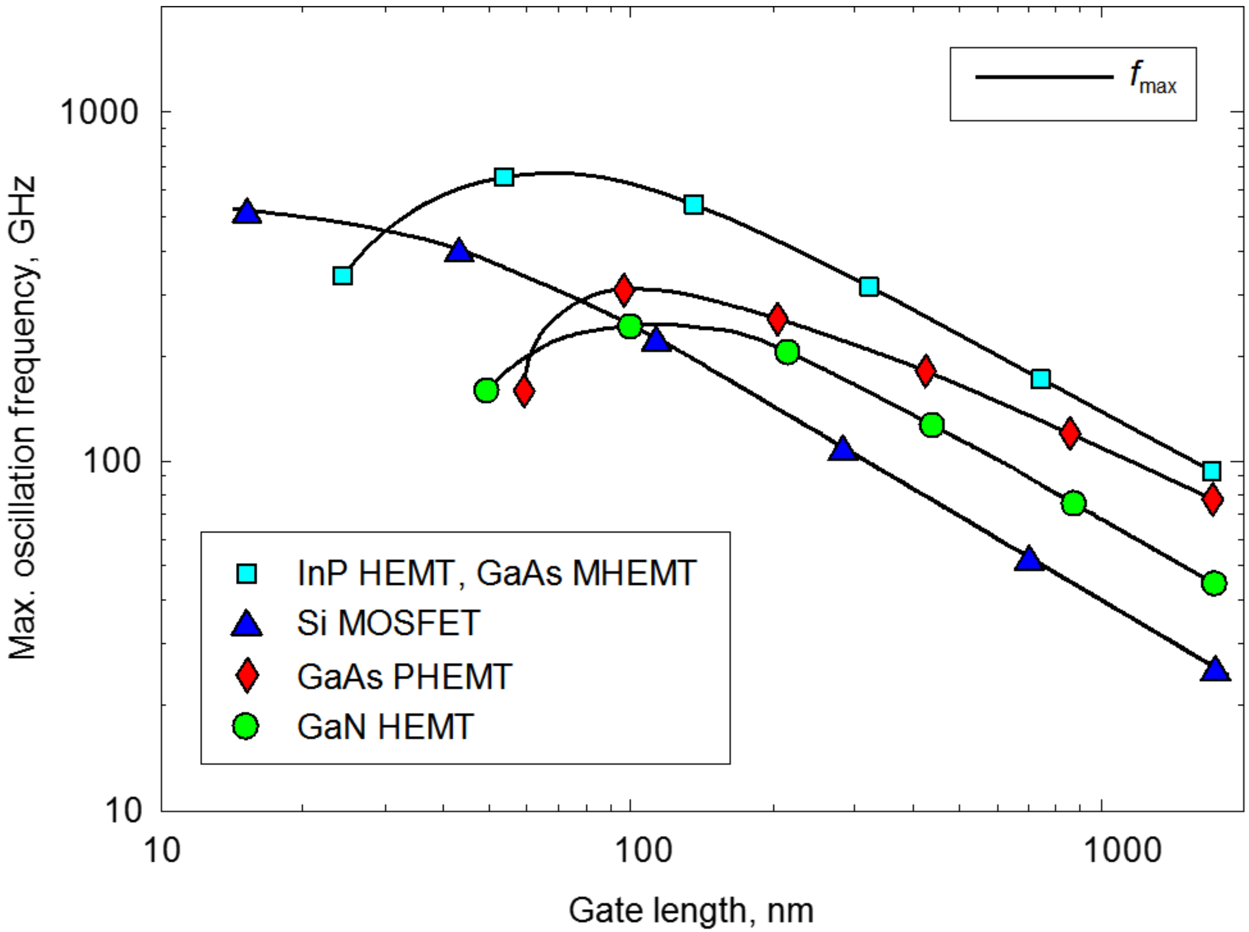
Technology evolution of nanometer MOSFETs: (a) conventional MOSFET with salicided polysilicon gate, low-doping drain double implant, 130 nm node; (b) strained Si channel MOSFET, 90-65 nm nodes; (c) strained Si channel, high-κ gate dielectric, metal gate MOSFET, 45-32 nm nodes; (d) Ultra thin body (UTB) SOI MOSFET, BOX is the Body Oxide, the gate length is 28 nm.

RF MOSFET limitatons: mobility, gate resistance, max. power

- MOSFET channel is low-mobility:
  - Low Si bulk mobility vs. III-V
  - Surface inversion channel → surface scattering
  - Consequence: lower current and transconductance → lower cutoff frequency
- Gate Resistance
  - Conventional nMOSFET → n+ poly gate ($r \sim 10^{-4}\ \Omega$cm), **small x-section**
  - Schottky gate FETs: metal gate ($r = 5 \times 10^{-6}\ \Omega$cm), **large (T or mushroom) x-section**
  - Large gate resistance deteriorates the **power gain** (*maximum frequency of oscillation*) and **minimum noise figure**

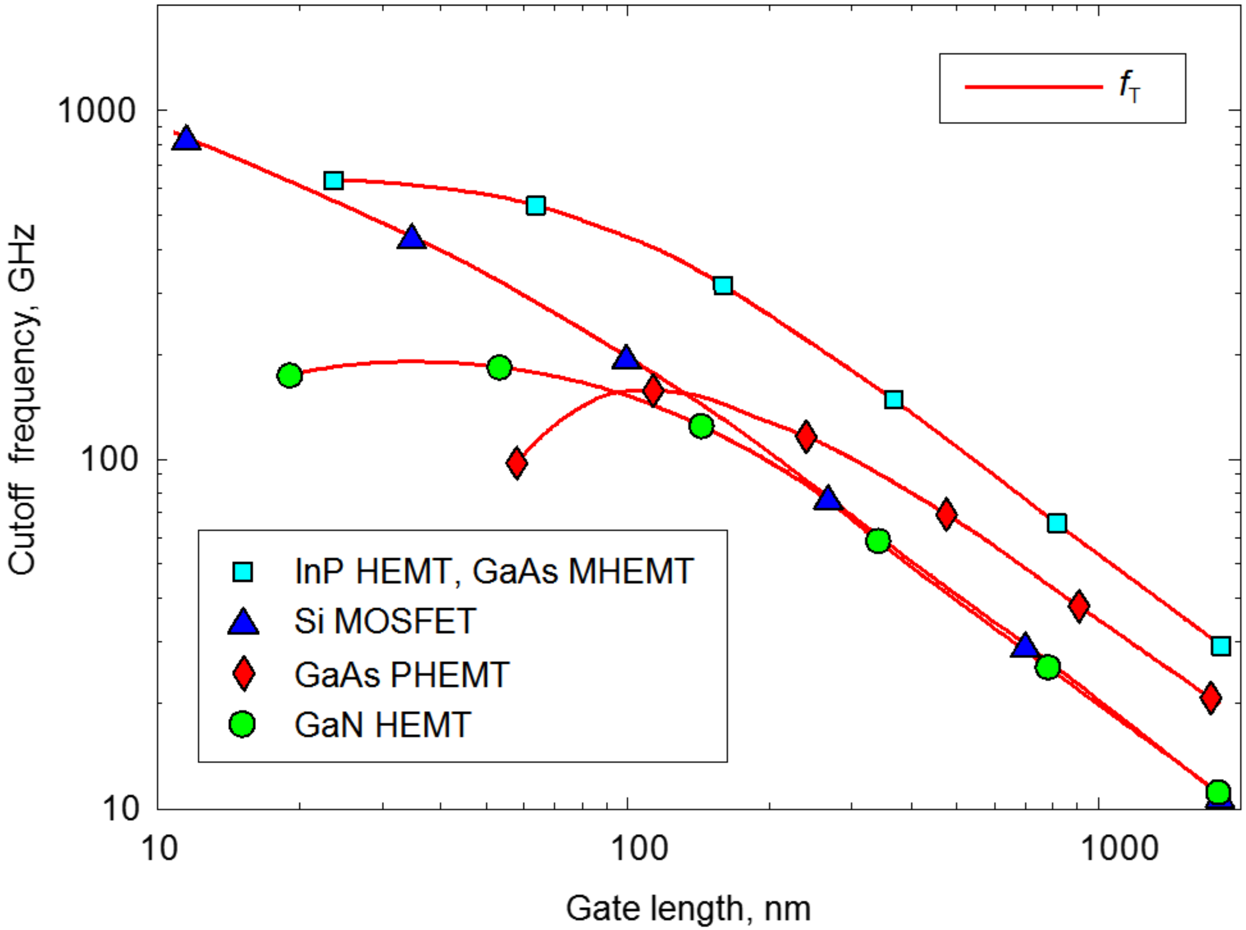
$$f_{\max} \propto \frac{1}{\sqrt{R_G}} \qquad \mathrm{NF}_{\min} \propto \sqrt{R_G}$$

Microwave FET performance overview



- InP HEMTs and GaAs mHEMTs are fastest
- GaAs pHEMTs: above 100 nm second-fastest, below 100 nm rapidly decline.
- GaN HEMTs: above 100 nm close to Si MOSFETs, below 100 nm saturate/decline.
- Si MOSFETs: astonishingly competitive, below 100 nm second fastest.

Microwave FET performance overview



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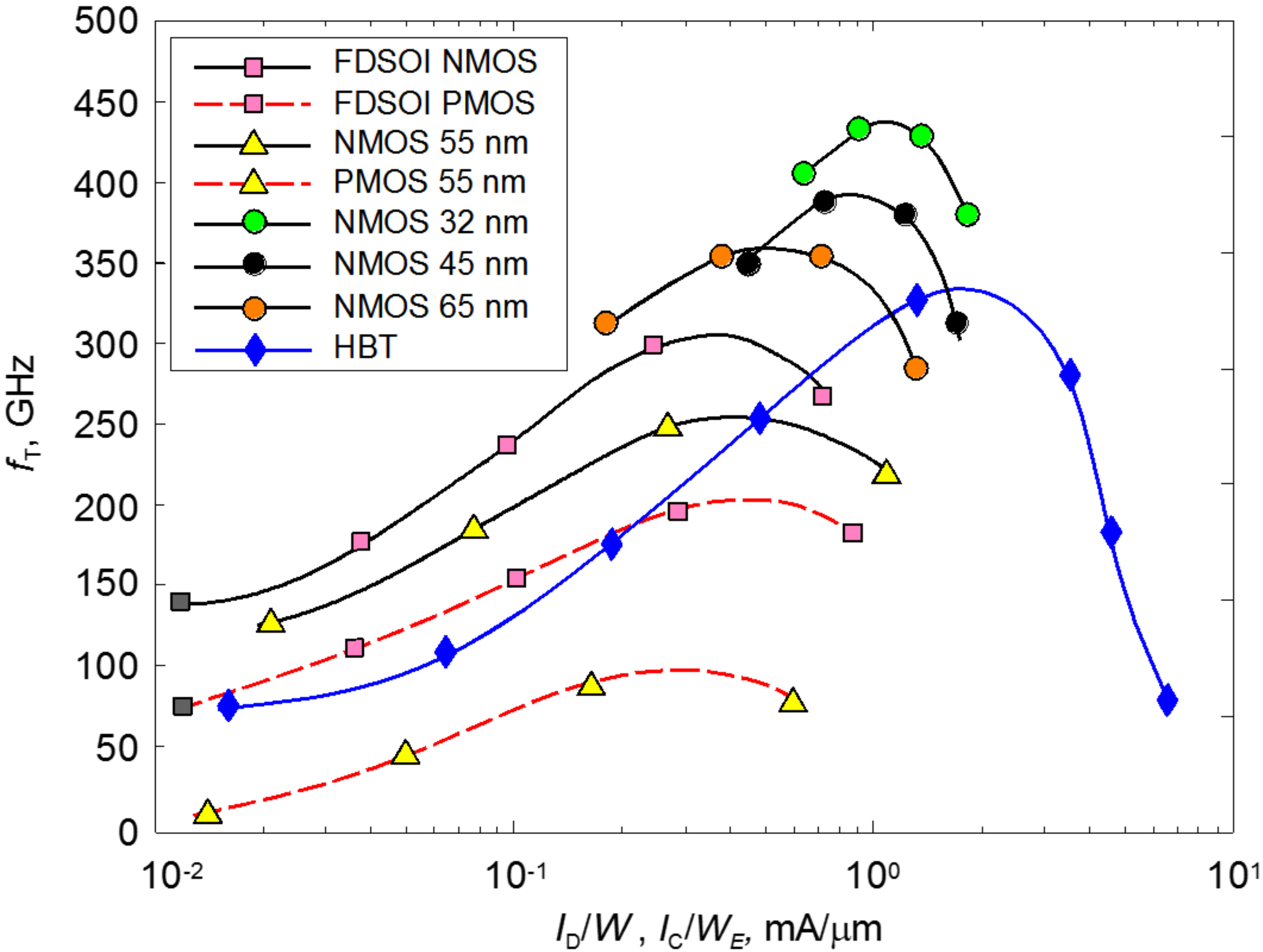
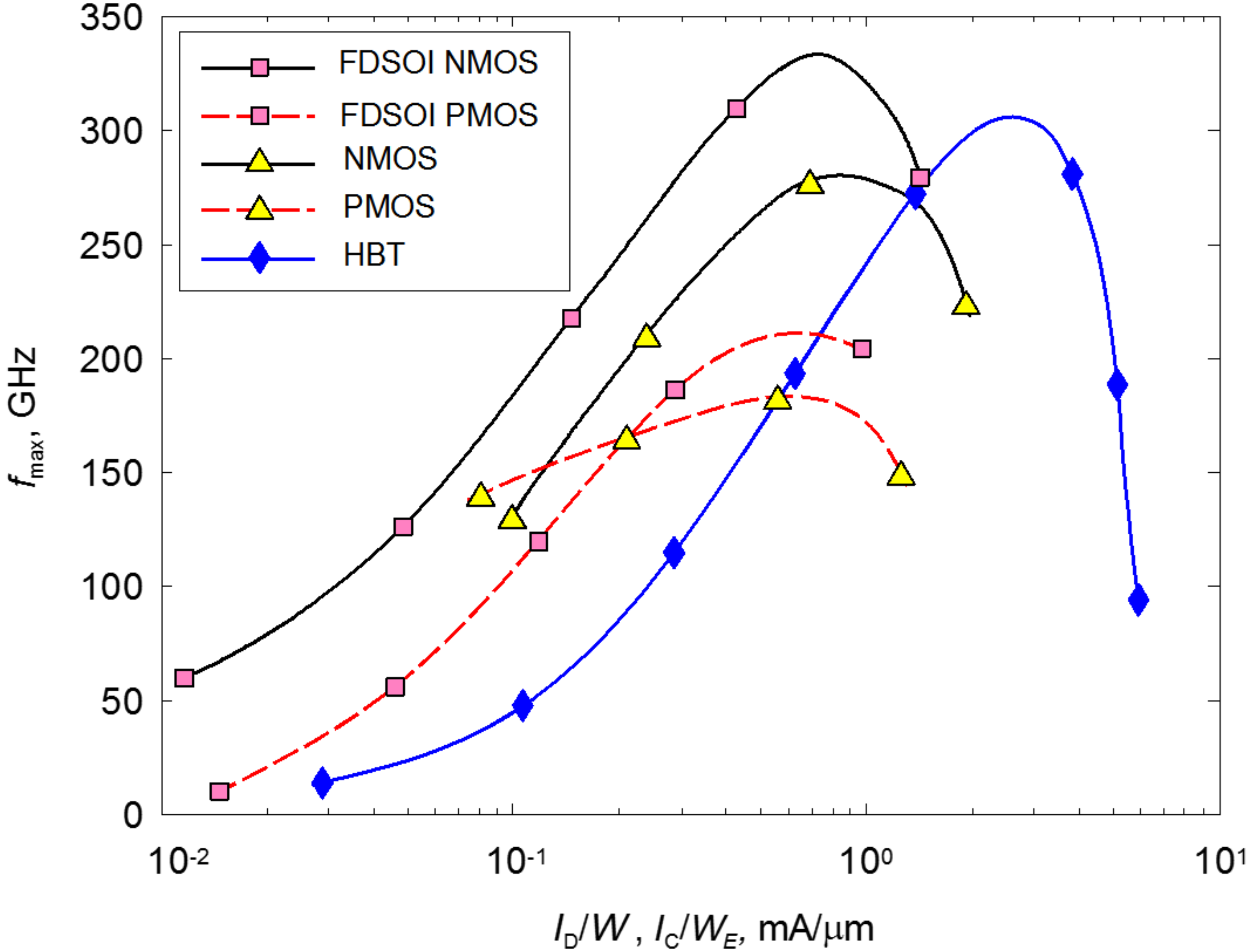
MOS – HBT family FT



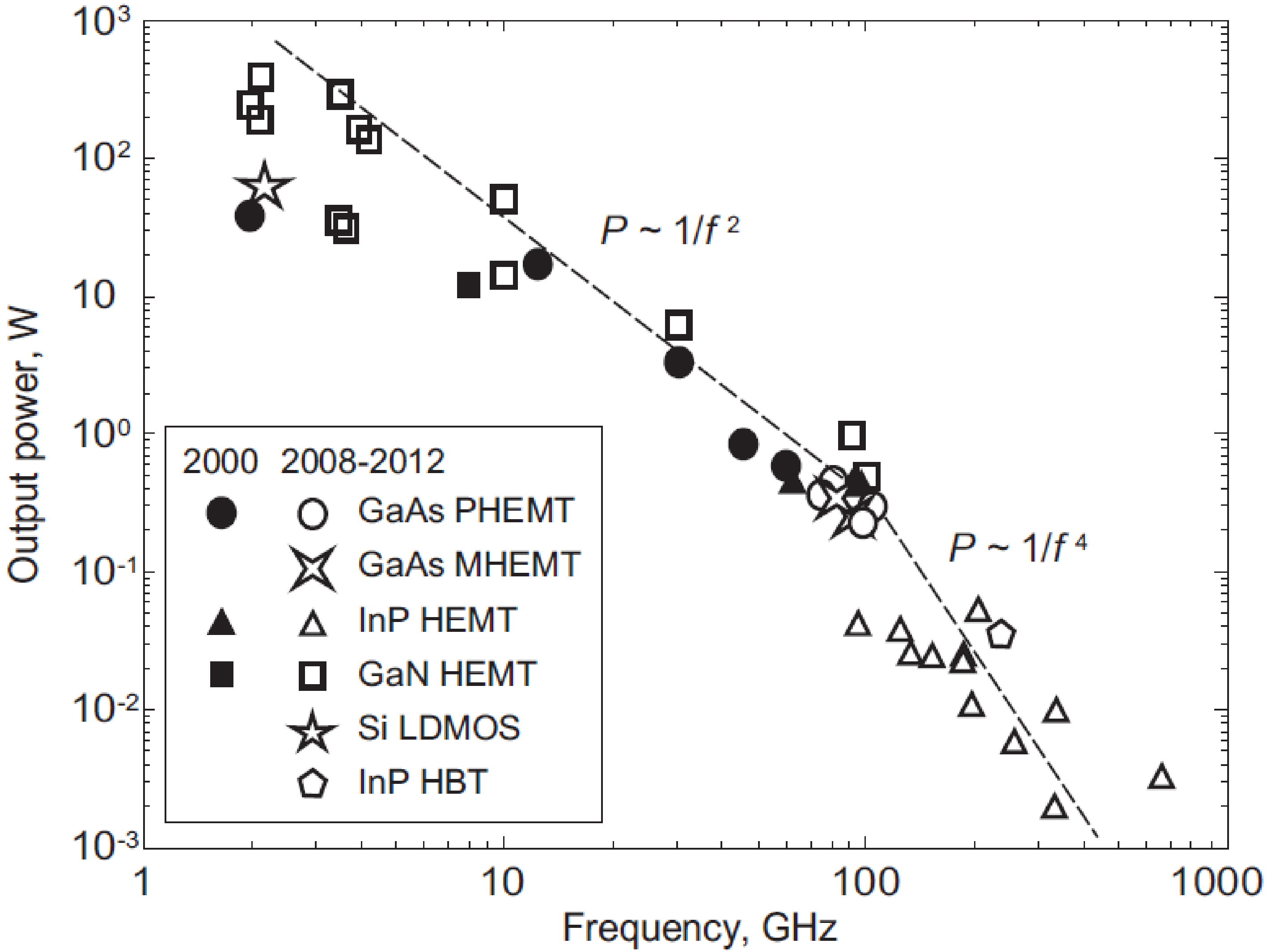
Cutoff frequency → the frequency at which the short-circuit current gain $|h_{21}|=1$

MOS – HBT family FMAX

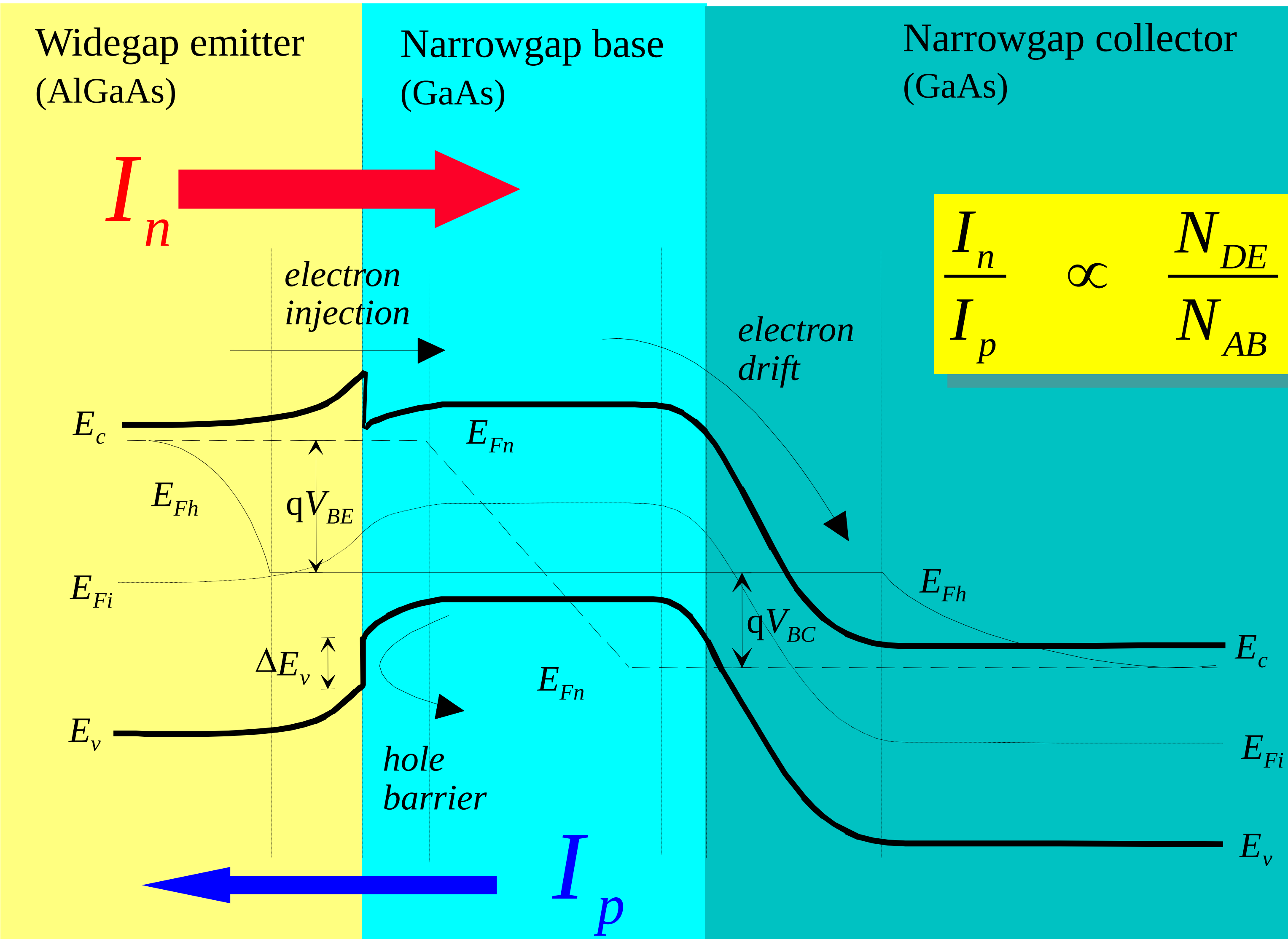


Maximum oscillation frequency → the frequency at which the max. available gain is MAG=1

Output power vs. frequency



Heterojunction Bipolar Transistors

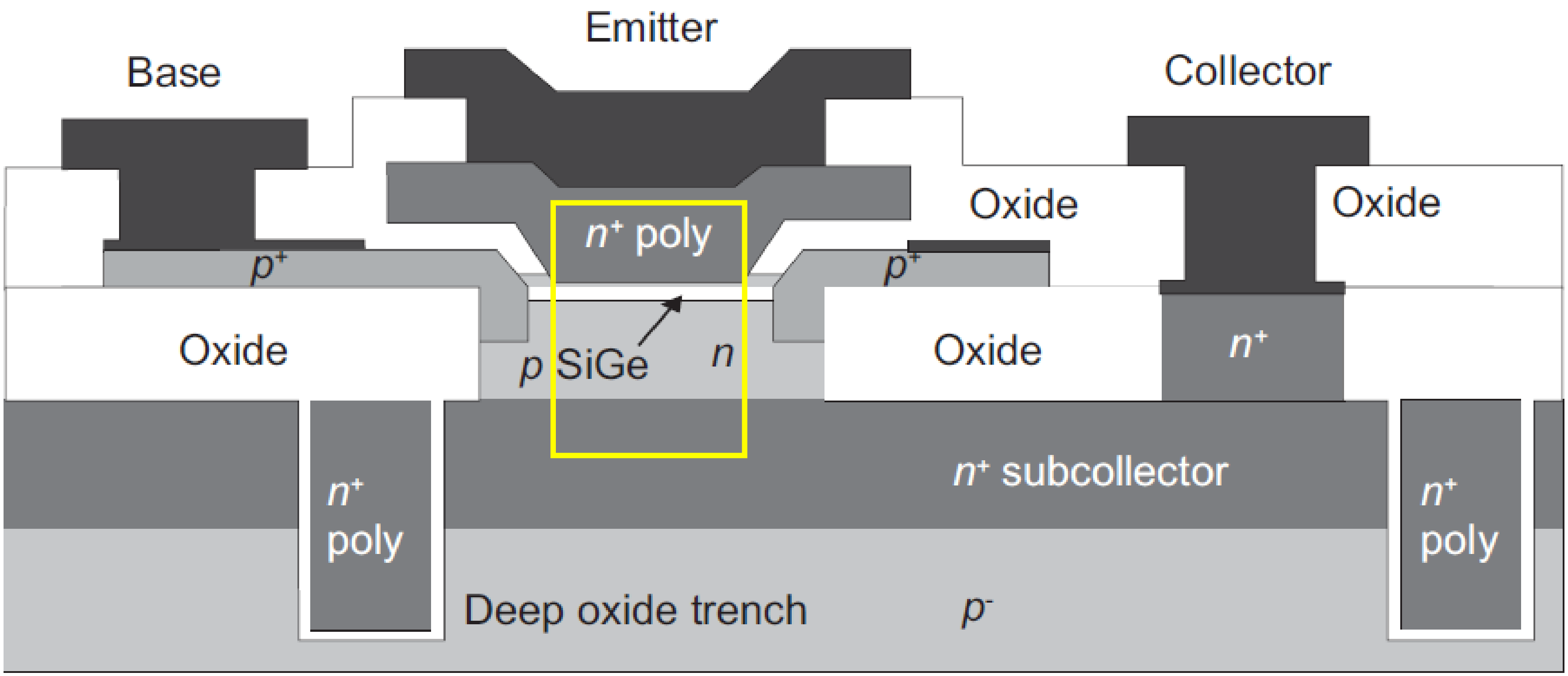


$$\frac{I_n}{I_p} \propto \frac{N_{DE}}{N_{AB}} \exp \frac{\Delta E_G}{k_B T}$$

HBT features

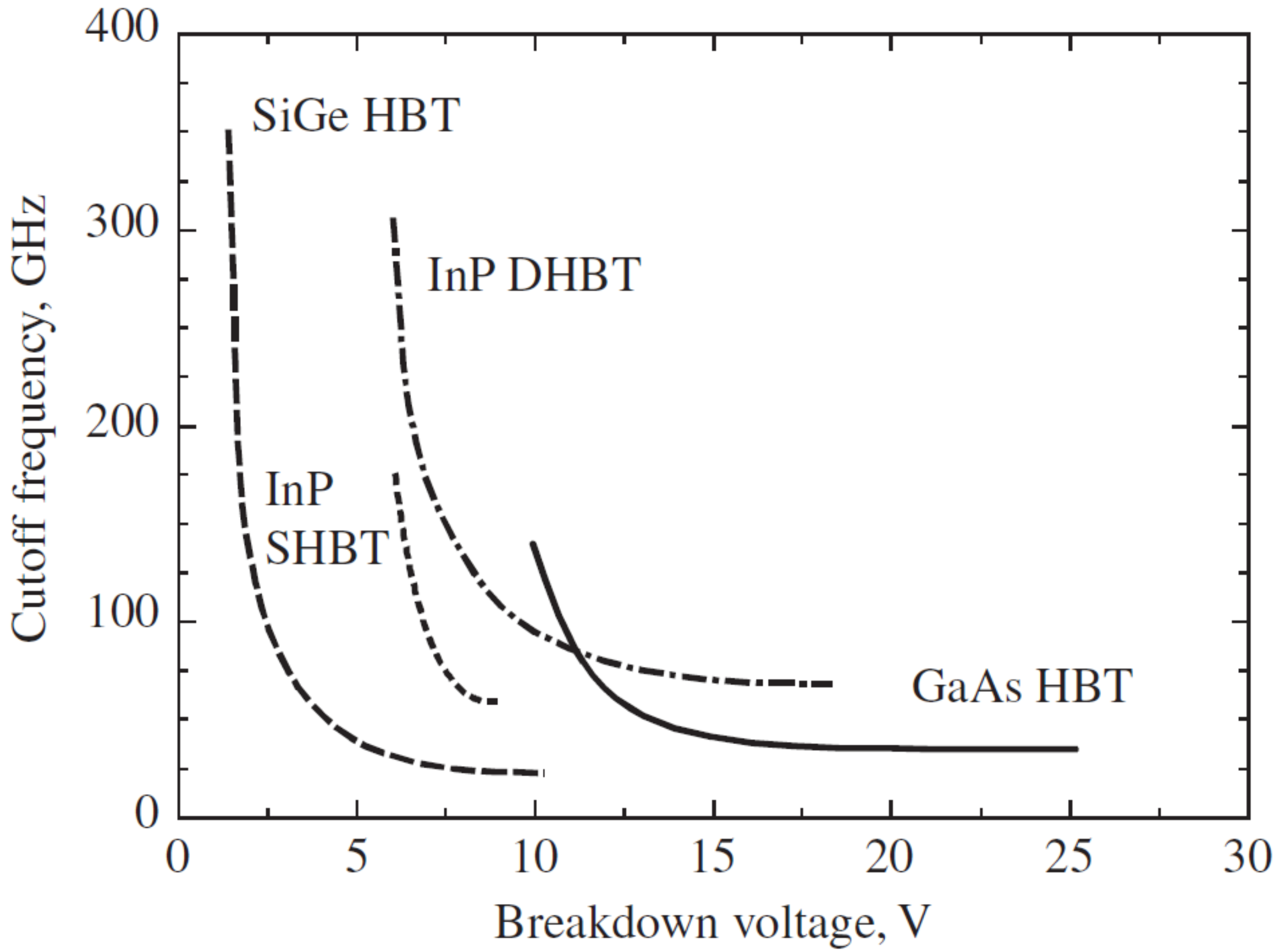
- HBTs use a narrowgap base and collector to allow base doping to be larger than emitter doping without compromising the emitter efficiency.
- Increasing the base doping lowers the base resistance, leading to an increase of the *maximum frequency of oscillation* (what is that?)
- High cutoff frequencies and low transit time obtained through thin epitaxial bases → very narrow emitter needed to decrease the base resistance
- Devices available on GaAs, InP, Si (SiGe)
- Operation up to 40 Gbps and beyond, however low breakdown voltage (3-4 V max.)

HBT on SiGe



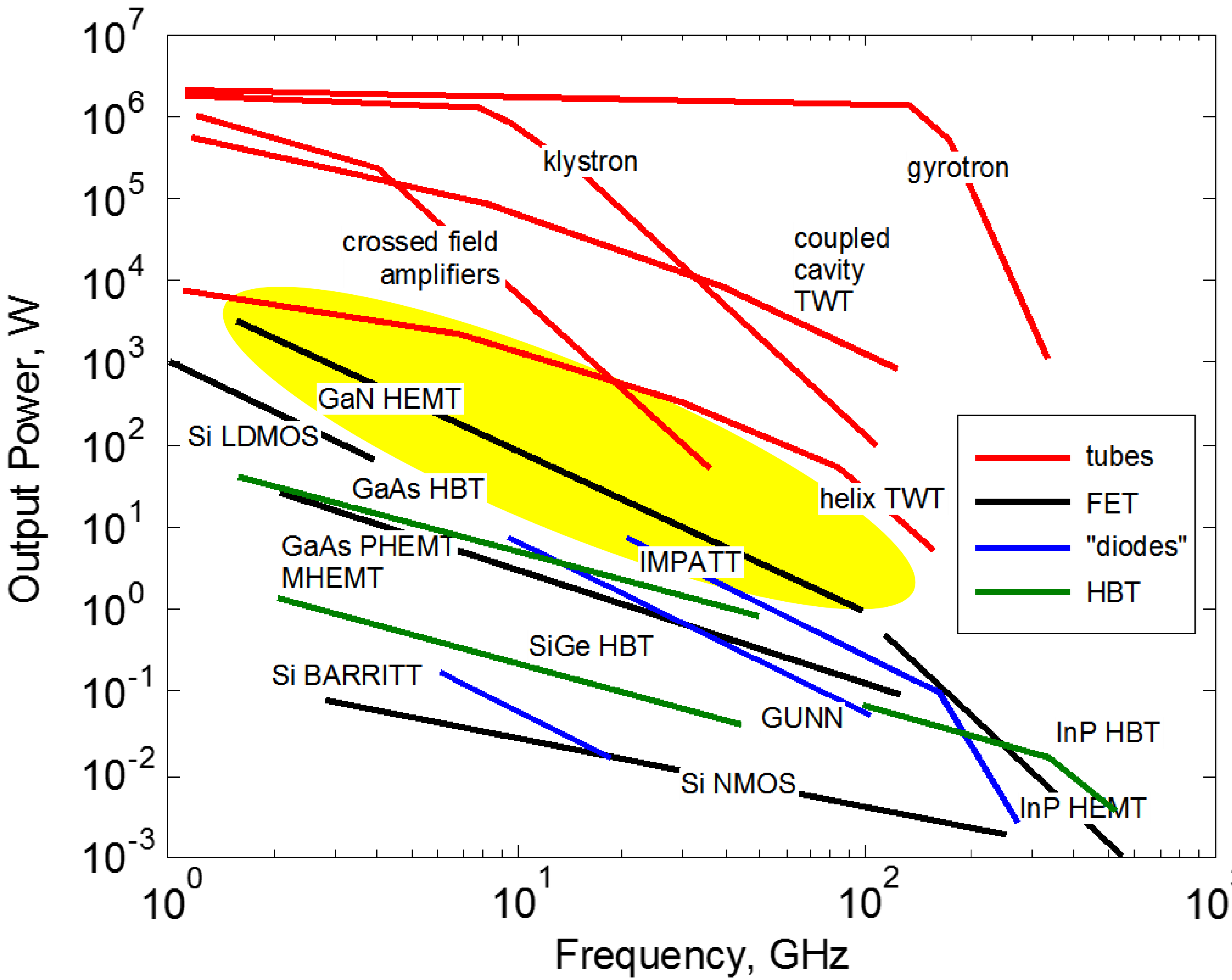
Emitter
Base
Collector
Oxide
Oxide
n+ poly
p+
p+
Oxide
p SiGe
n
Oxide
n+
n+ subcollector
n+ poly
n+ poly
Deep oxide trench
p-

SiGe vs. III-V frequency-breakdown tradeoff

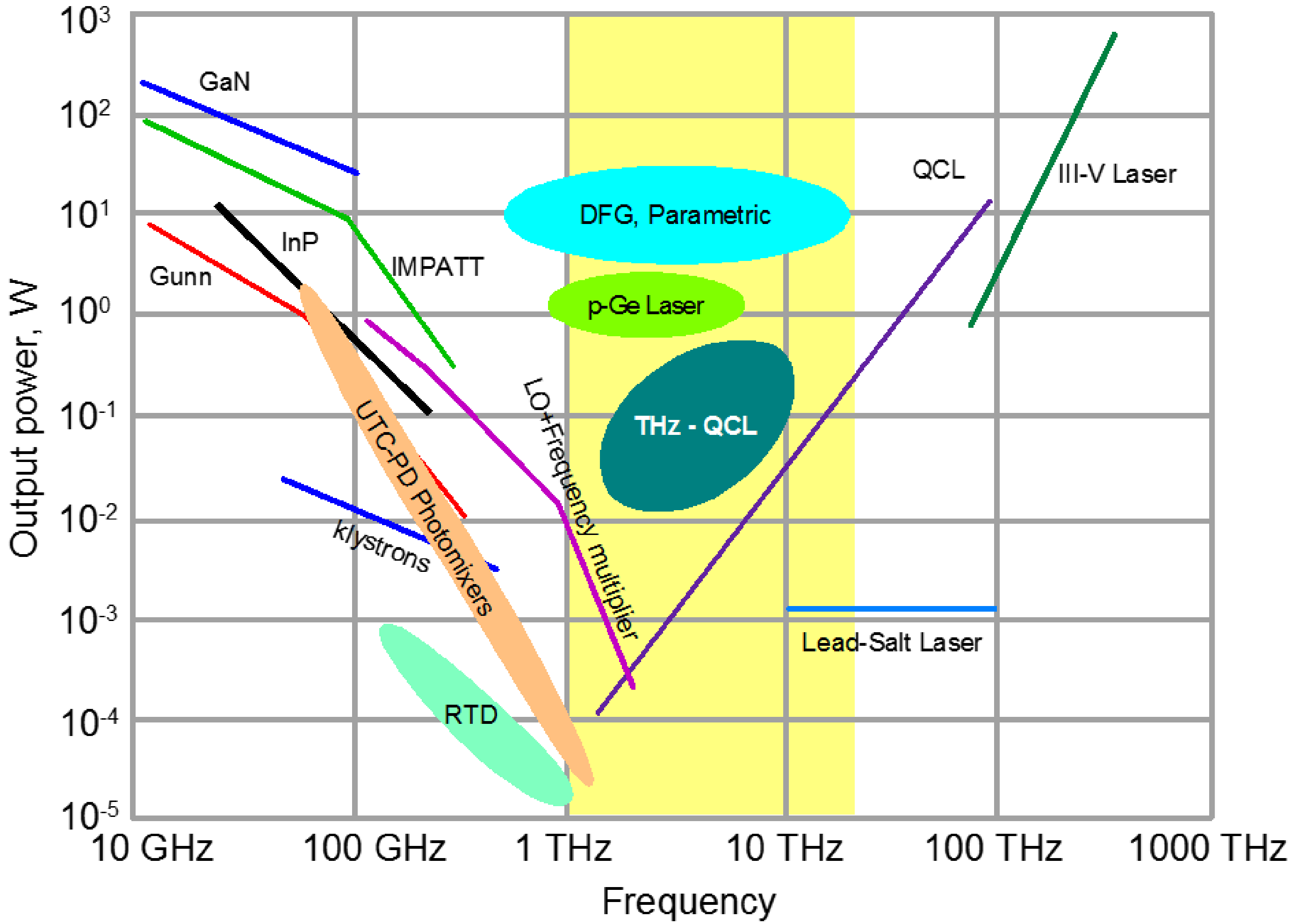


High-frequency SiGe → very low breakdown voltage → no power amplifiers (from Fig. 6.61, G.Ghione, *Semiconductor Devices for High Speed Optoelectronics*, Cambridge 2009)

In praise of vacuum tubes



The THz gap



Adapted from: *Recent advances in terahertz science at Queen Mary University of London* - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/261096257_fig1_Fig-1-Picture-of-the-THz-gap-circa-2011-4

Which is which…

- IMPATT, Gunn → microwave diodes, oscillators
- UTC-PD →UniTraveling Carrier Photodiode
- QCL → Quantum Cascade Laser
- DFG → Difference Frequency Generation exploiting the parametric effect
- P-Ge Laser → a solid-state laser exploiting intersubband transitions (liquid He operation)
- RTD → Resonant Tunneling Diode