Section 1.2

CLASSIFICATION, LIMITATIONS AND DIFFERENCES OF RF SOURCES

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

Literatur Chapter 1.2

Karlsruher Institut für Technologie

Shulim E. Tsimring, **Electron Beam and Microwave Vacuum Electronics**,
John Wiley & Sons, New Jersey 2007

M. Hein, **Schaltungen und Bausteine der HMT,**
TU Ilmenau

Gilmour, A. S., Jr., **Microwave Tubes**,
Artech House, Norwood, MA, 1986

Ingmar Kallfass **Vorlesung Hoch-und Höchstfrequenzhalbleiterschaltungen**
Skript 2014

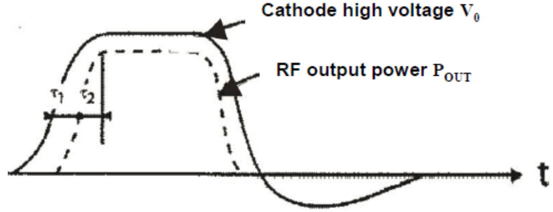
Definition: Oscillator

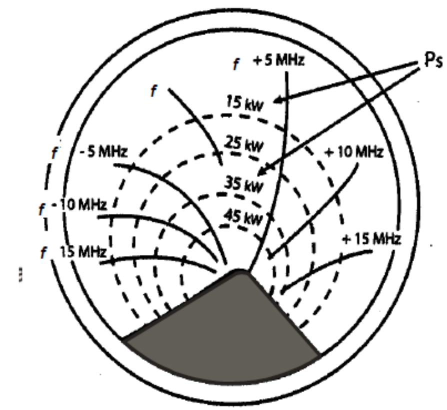
Power Supply	$P_0 = V_0 I_0$
Filament Power	$P_F = V_F I_F$
Focusing Magnet Power	P_{FOC}
Drive Power	P_d (Amplifier)
Output Power	P_{OUT}

Oscillator:

τ_1: **Starting time**
τ_2: **Rise time**

$\Delta f/\Delta I_0$: **Pushing**
$\Delta f/\Delta \Phi_L$ **(VSWR constant): Pulling**





Rieke Diagram

$$\eta = P_{out} / \left(P_F + V_0 I_0 + P_{FOC} \right)$$: „overall tube efficiency“

$$\eta_{\text{interaction}} = P_{out} / V_0 I_0$$: interaction efficiency“

Main issues for oscillators are **spurs**, **phase noise**, **frequency drift**.

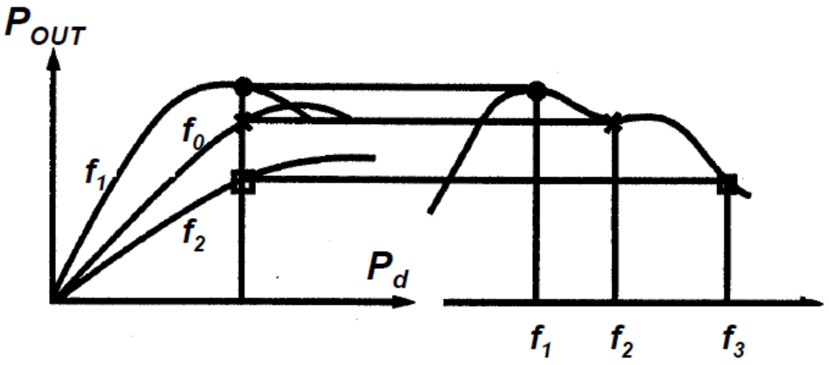
Additionally we face **frequency pulling** and **frequency pushing**

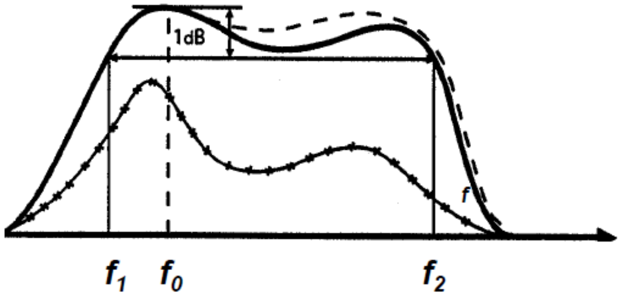
Oscillator: Frequency Pushing and Pulling

Frequency Pushing:
Every oscillator needs typically a DC power supply. Unfortunately, the operating frequency ω0 of an oscillator is sensitive to this supply voltage. In other words, as the D.C. supply voltage changes, the output frequency can also change. We call this phenomenon **frequency pushing**.

Frequency Pulling:
The output of an oscillator will always be attached to a load. The impedance of this load will affect the operating frequency of the oscillator! As Γ_L changes, so can the frequency ω_0 (e.g., $\omega_0(\Gamma_L)$). This phenomenon is called **frequency pulling**.

Definition: Amplifier





Power amplifier gain and efficiency

$$\eta = P_{out} / \left(P_F + V_0 I_0 + P_{FOC} + P_d \right)$$

$$\eta_{Wechselwirkung} = P_{out} / V_0 I_0 \quad \text{: Interaction efficiency}$$

$$G = 10 \cdot \log_{10} \left(P_{out} / P_d \right) \quad \text{: Gain}$$

Regarding the bandwidth following definitions are valid:
- **1 dB Bandwidth** defined by the decreasing output power
- **3 dB Bandwidth**

Typically the gain curve P_{out}/P_d shows a linear behavior for small input signals.

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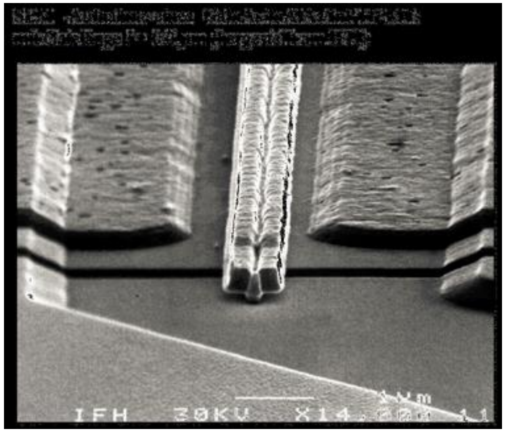
Vacuum Electronics vs Semiconductor Electronics (II)

Attribute	Semiconductor	Tubes
Carrier	bound	free
Velocity of the Carrier	≈ 0.001 *c*	≈ 0.1 *c* (factor 100)
Dielectric Constant	>1 ... 11	1
Interaction Mechanism	voltage and charge	external fields (***E*** and ***B***)
Adjustment	quasi 1-dim	3-dim
Functionality	doping	electrodes
Size	µm^3	cm^3 (×10^{12})
Power range	W … kW	kW… MW (×10^3)
Efficiency	1…30 %	10…80 %



Characteristic for High Power-Semiconductor Elements

- High breakdown voltage
- High current/power density
- Excellent thermal conductivity
- Low drain-source capacity
- Low bulk resistance
- High live time

High Frequency Semiconductor Devices

- Semiconductors are:

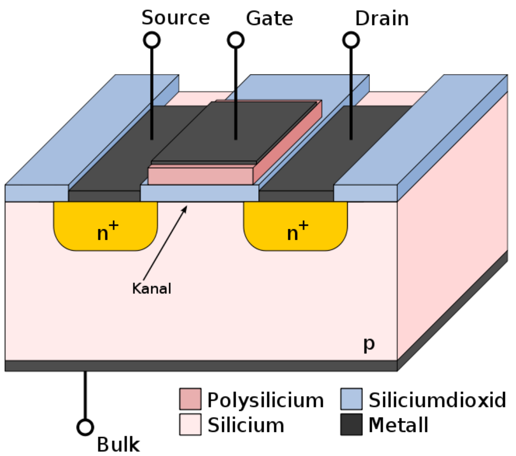
Elements of the 4th main group (MG)	IV
Composites of the 4th + 4th MG	IV-IV
Composites of the 3rd + 5th MG	III - V
Composites of the 2nd + 6th MG	II – VI

Periodensystem

- HEMT: High Electron Mobility Transistor
- (D-) HBT: (Double) Hetero-Structure Bipolar Transistor
- CMOS: Complementary Metal-Oxide-Semiconductor
- MOSFET: Metal Oxide Semiconductor FET
- MESFET: Metal Semiconductor FET

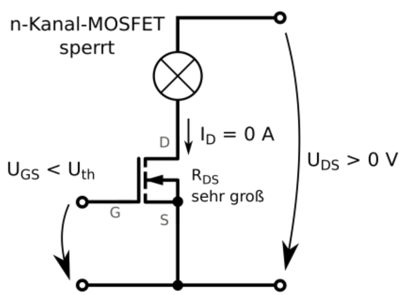
	Field Effect Transistor (FET)	**Bipolar Junction Transistor (BJT)**
III-V-based	GaAs HEMT InP HEMT GaN HEMT	GaAs HBT InP (D-) HBT
Si-based	(RF-) CMOS	SiGe HBT

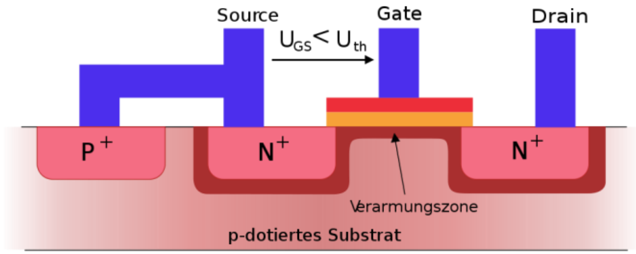
MOSFET: Functional Principle

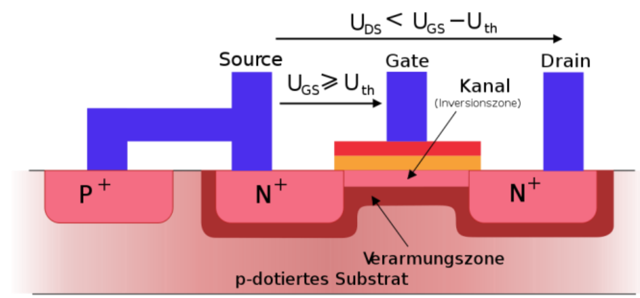


Goal: High gain and short current time

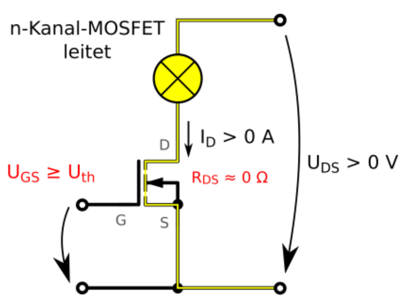
1. Strong doping in the channel (high conductivity)
2. Small gate length (short transit time)
3. Optimized channel width
4. Small parasitic elements

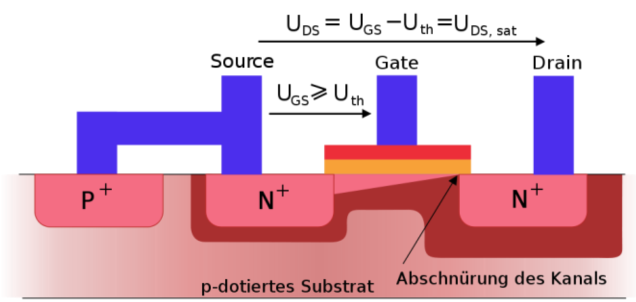




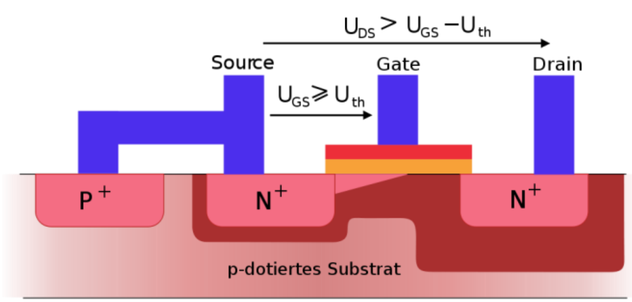


linearer/ohmscher Bereich





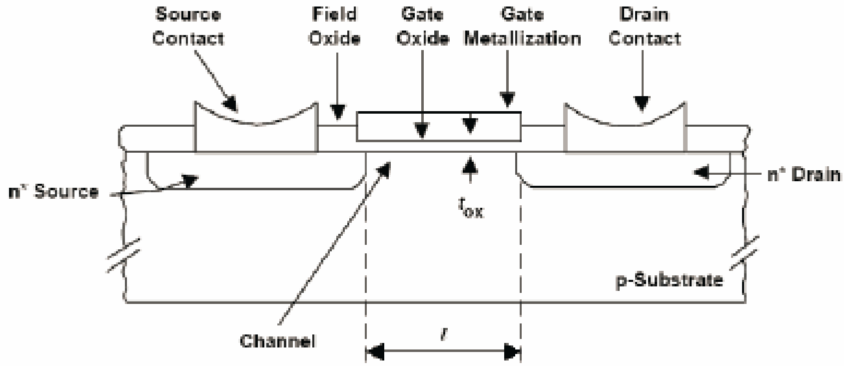
Abschnürung (Übergang zum Sättigungsbereich)



Sättigungsbereich

Dominating Types

MOSFET



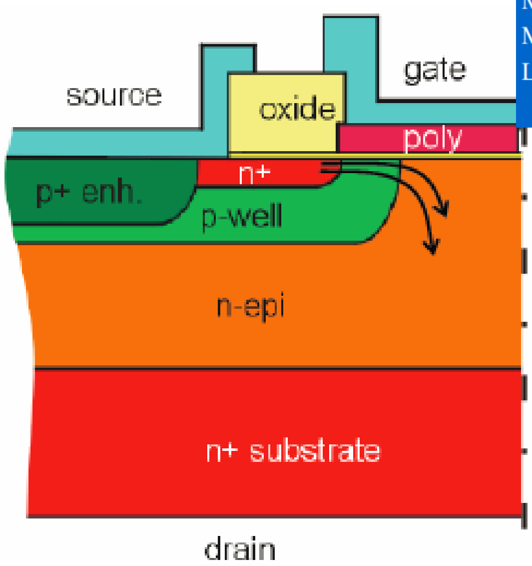
VDMOS
- Higher Input Impedance
- More Rugged
- More Stable
- High Power 600W

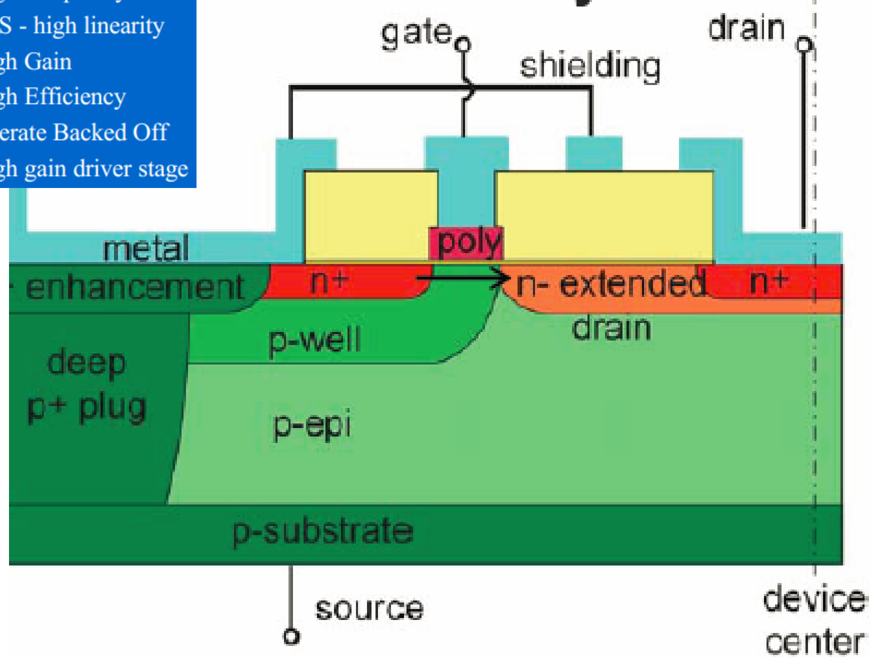
LDMOS
- Low Crss - Better output input isolation.
- High Gain.
- High Efficiency @ high Freq.
- High Frequency - > 2 Ghz

VDMOS
Vertical Doubly Diffused

VDMOS	LDMOS
Broad Band	Narrow Band
Raw Power	High Frequency
CW - FM / AM	PCS - high linearity
More rugged	High Gain
More stable	High Efficiency
Lower Frequencies	Operate Backed Off
	High gain driver stage

LDMOS
Lateral Doubly Diffused





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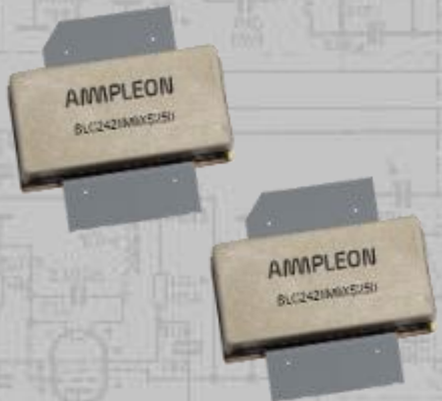
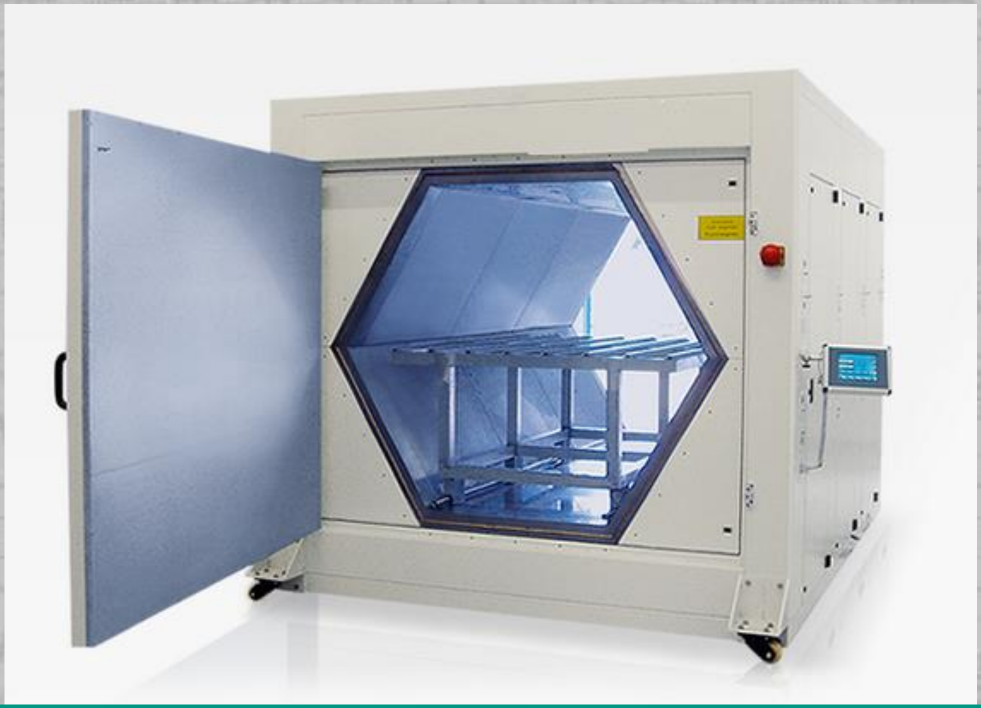
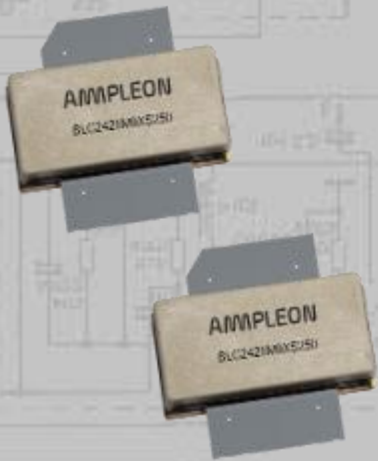
Application LDMOS
Distributed RF - Sources







Up to 32 distributed RF - Sources

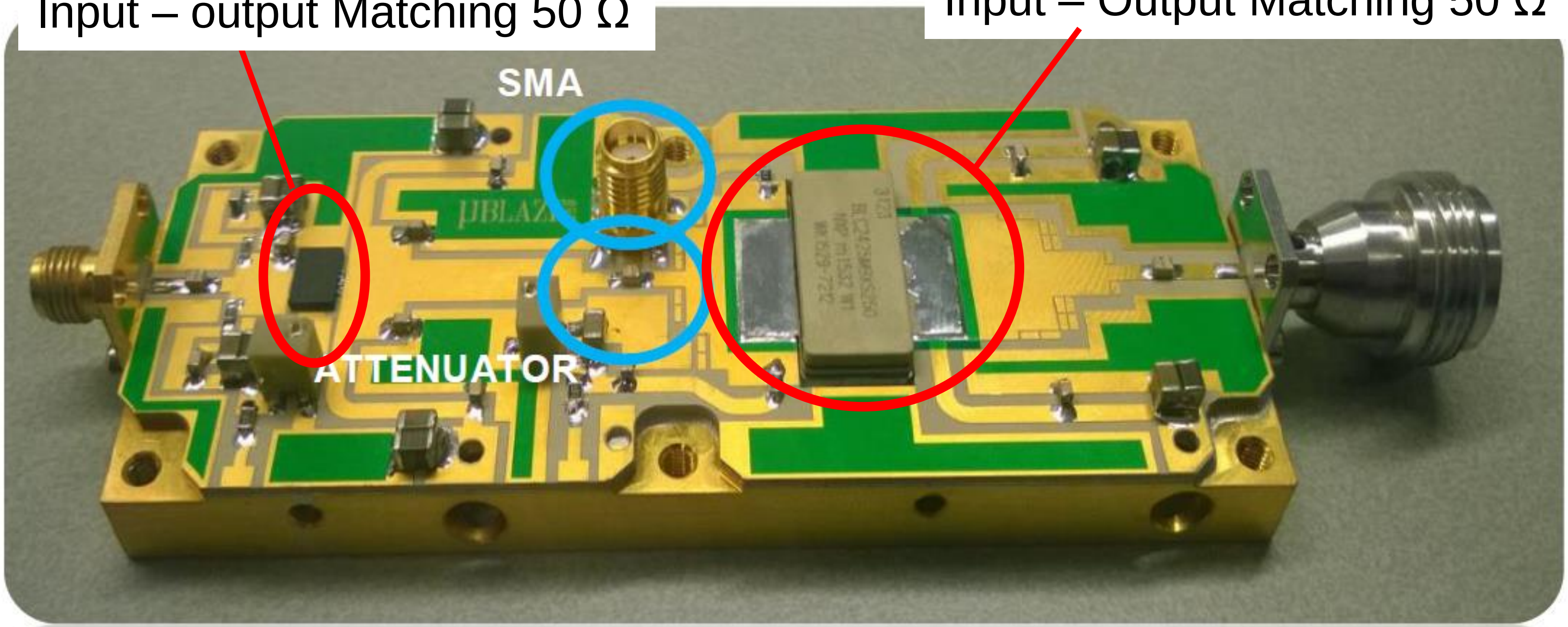
- Key features and benefits
  - Faster uniform drying
  - Excellent ruggedness
  - Thermal stability
  - Efficiency saving

- Benefits
  - Controllability feedback loop
  - Heat spread evenly across target
  - Improved product quality
  - Unprecedented system reliability

LDMOS Application

Driver amplifier
Gain: 18 dB
Output power: 10 W
Supply Voltage: 32 V
DC – Current: 1 A
Input – output Matching 50 Ω

Final amplifier
Gain: 18 dB
Output power: > 250 W
Efficiency: 58 % @ 2.45 GHz
Supply Voltage: 32 V
DC – Current: 16 A
Input – Output Matching 50 Ω



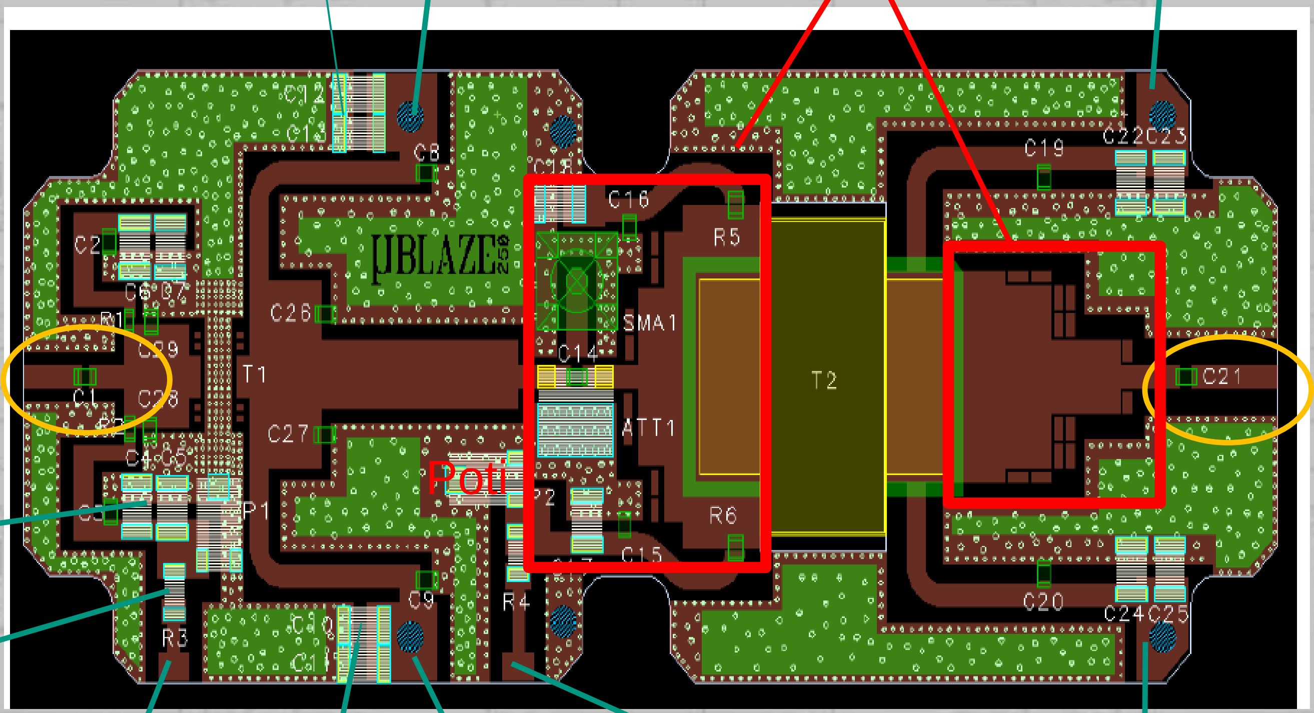
Application LDMOS Board

RF – DC decoupling

Vds = 32 V

Matching

Vds = 32 V



DC – Block 15 pF

DC – Block 15 pF

RF – DC decoupling

Voltage divider

Vgs = 4 V

Vds = 32 V, saturation

Vgs = 4 V

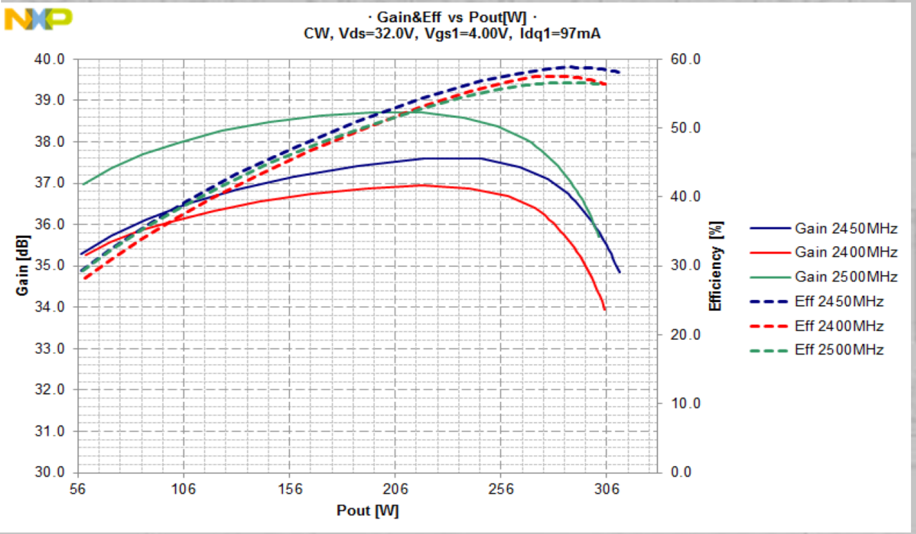
Vds = 32 V

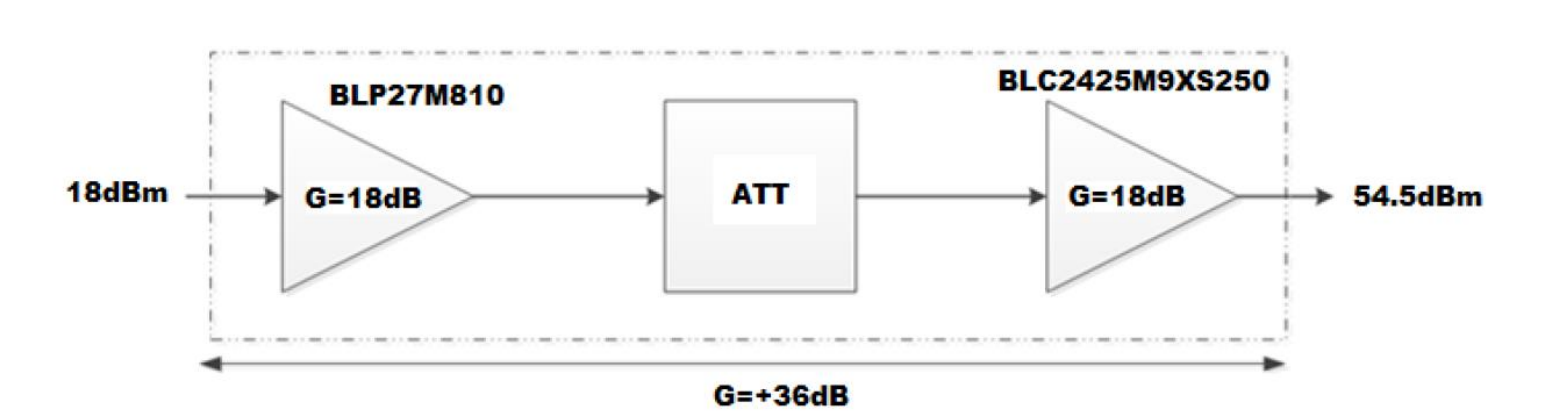
RF – DC decoupling

LDMOS Application

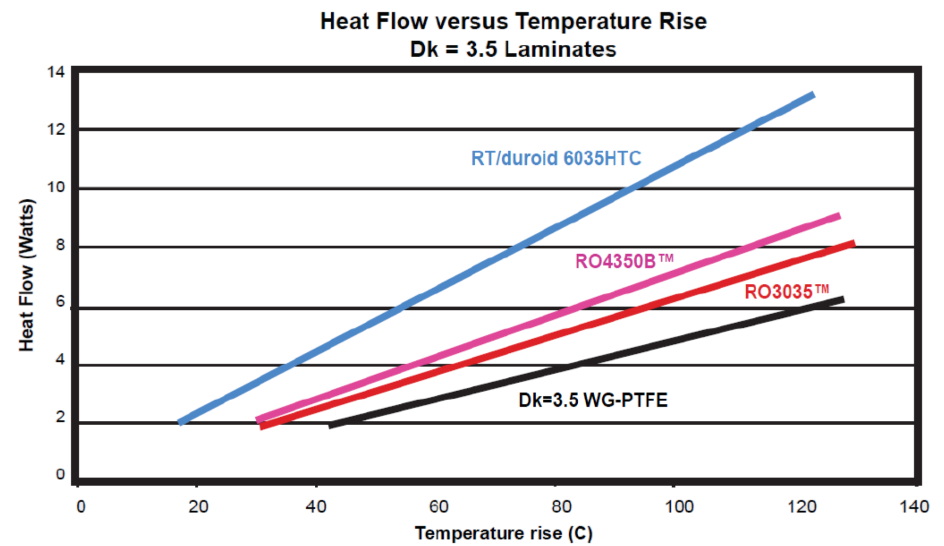
Description, unit	Min	Typical	Max	Condition / Remark
Frequency band, GHz	2.40	2.45	2.50	ISM frequency band
Input power, dBm	16	18	20	For P-1dB compression
Output power, dBm	54.0	54.5	55.0	P-1dB compression; 280, 320, 350 W
Gain, dB	34	36	38	P-1dB compression
Gain flatness, dB	0.5	1.0	2.0	P-1dB compression
Efficiency, %	55.0	58.0	-	P-1dB compression
Input Return Loss, dB	-	-10	-	P-1dB compression
Harmonics, dBc	-	-40.0	-	Level of each harmonic component

Freq [MHz]	P1dB [dBm]*	P1dB [W]*	Eff@P1dB [%]*
2400.00	54.5	282.38	57.5
2450.00	54.6	290.57	58.8
2500.00	54.4	276.57	56.5





Application LDMOS
PCB Material / Rogers duroid 6035HTC



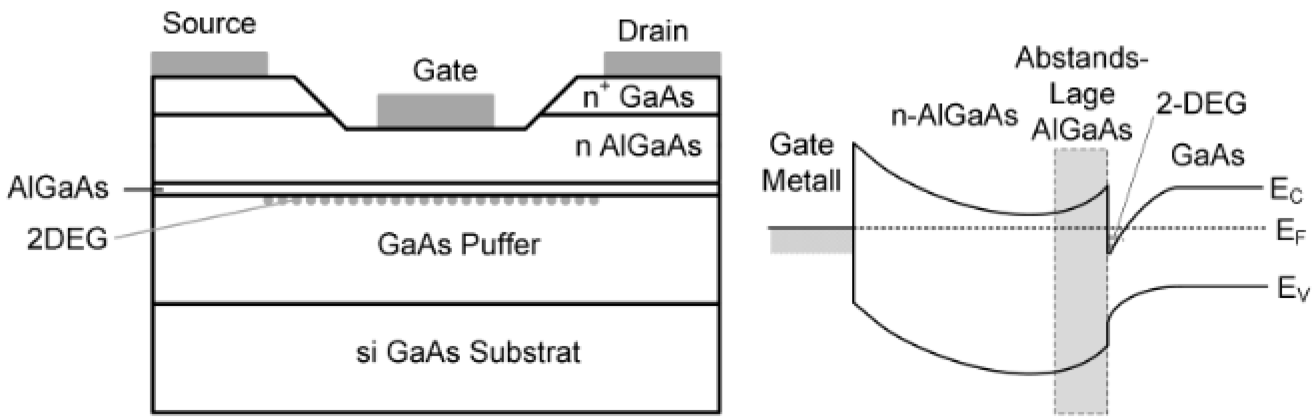
Rogers duroid 6035 HTC

- High thermal conductivity
  - Improved dielectric heat dissipation enables lower operating temperatures for high power applications
- Low loss tangent
  - Excellent high frequency performance

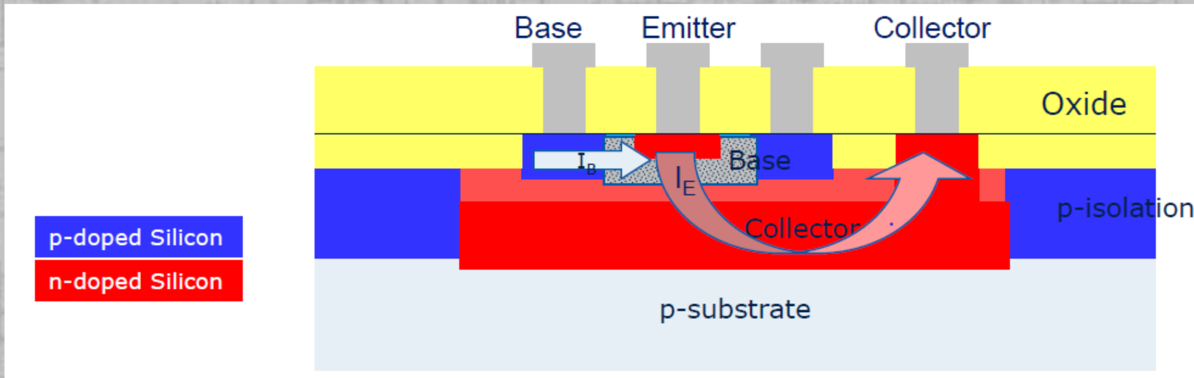
Dominating Types

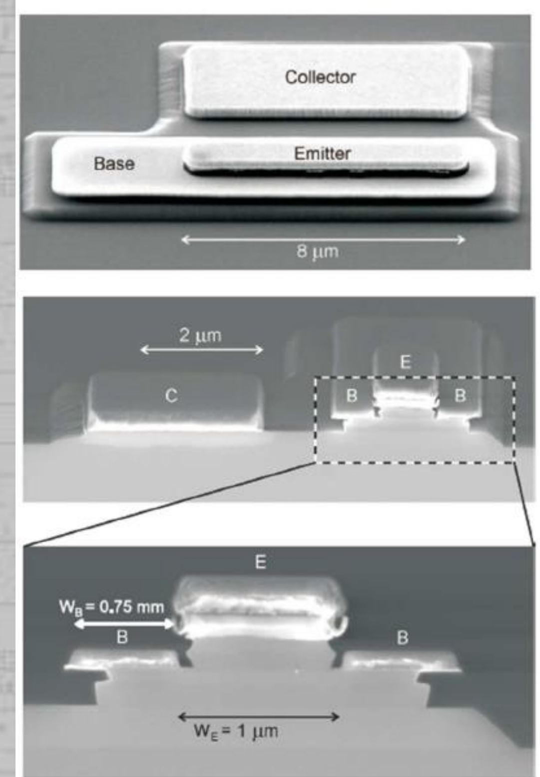
High Electron Mobility Transistor (HEMT)

- Physically separate ionized donor atoms and free electrons → heterostructure
- The channel is located in undoped region → low scattering → high mobility
- The carriers (electrons) are provided by doped supply layer
- Gate voltage controls carrier density in the channel
- Lattice matched, pseudomorphic, metamorphic



Dominating Types





IAF InP DHBT

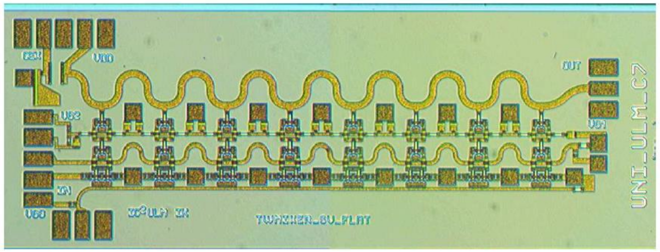
Heterojunction Bipolar Transistor (HBT)

- Emitter is composed of a larger band gap material than base → band gap difference
  - Barrier for holes to inject into the base = larger
  - Barrier for electrons to inject into the base = low
  - → reduces minority carrier injection from the base when the emitter-base junction is under forward bias
  - → reduces base current and increases emitter injection efficiency
- Commonly used HBTs

Dominating Types

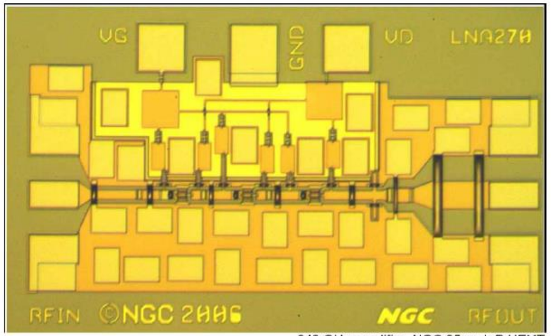
GaAs HEMT

- Features
  - The „classic“ HEMT technology
  - Many foundries worldwide
  - Analogue frontends (incl. LNA, mixer, PA) up to >100 GHz
- Major Applications
  - Automotive + military radar
  - communication



InP HEMT

- Features
  - + highest MMIC performance to-date
  - - InP substrate: max 4“, costly
- Major Applications
  - Ultra low-noise amplifier
  - Analogue frontend beyond 100 GHz

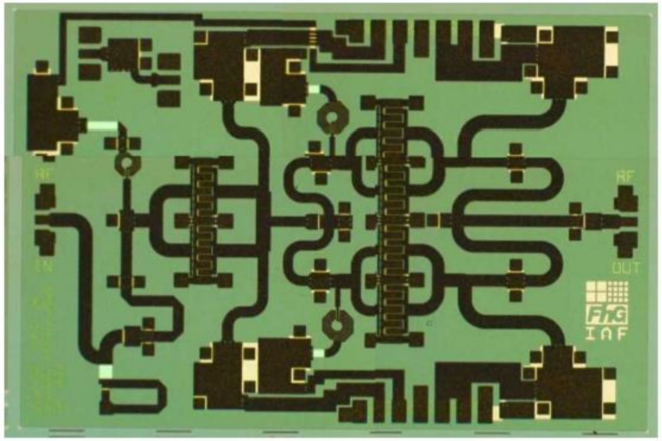


340 GHz amplifier, NGC 35nm InP HEMT

Dominating Types

GaN HEMT

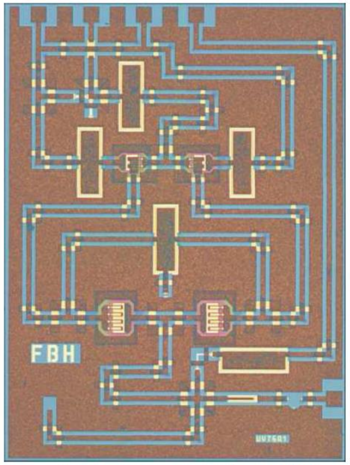
- Features
  - High breakdown voltage
  - High speed
- Major MMIC Applications
  - High efficiency and broadband power amplifiers
  - Base stations
  - Radar



GaN X-band (10 GHz) power amplifier

GaAS HBT

- Features
  - High breakdown voltage
- Major MMIC Applications
  - Power amplifiers
  - Low phase-noise frequency sources (VCO)

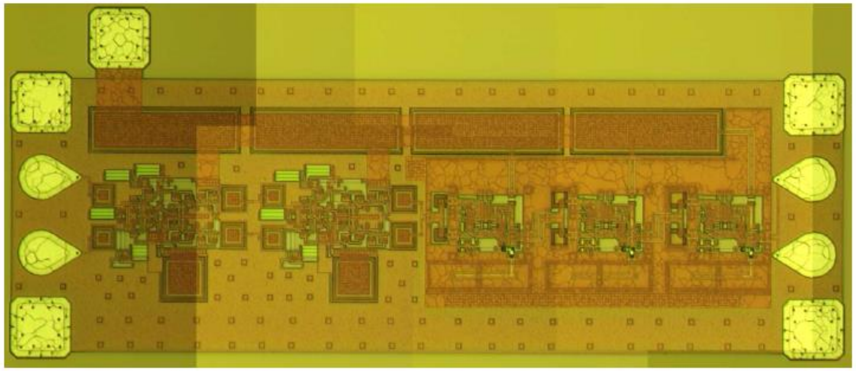


76 GHz VCO, GaAs HBT FBH Berlin

Dominating Types

SiGe HBT

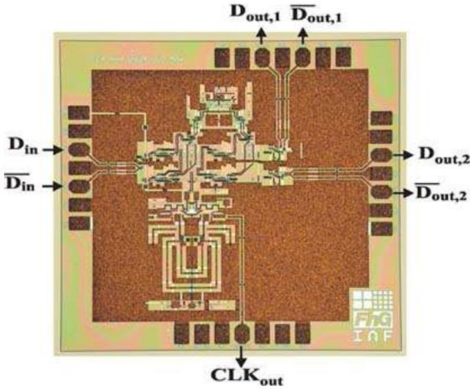
- Features
  - High frequency capability
  - High integration density
- Major MMIC Applications
  - Analog up to 77 GHz
  - Mixed signal: e.g. fast ADC/DAC



>40GHz 32:1 frequency divider (Chartier, Atmel SiGe HBT)

InP HBT

- Features
  - High breakdown voltage
- Major MMIC Applications
  - Mixed-signal circuits
  - Optical communication systems (100 Gbit Ethernet)

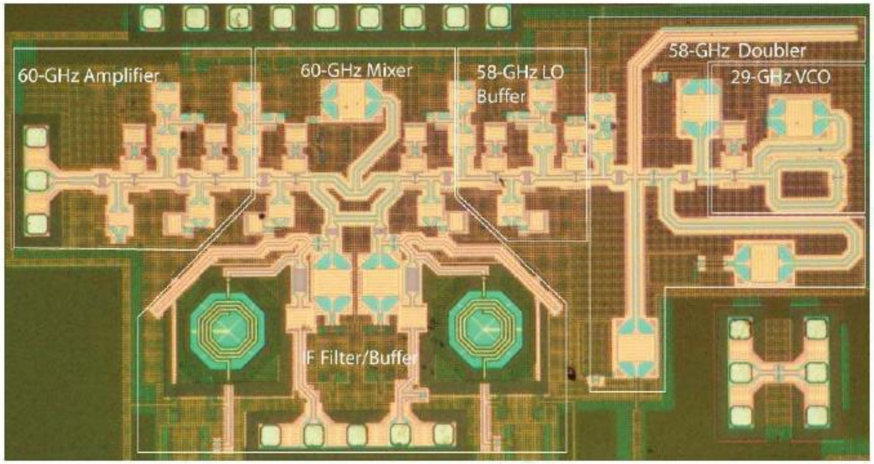


InP DHBT 80Gbps clock and data recovery

Dominating Types

(RF-) CMOS

- Features
  - Fast increasing high frequency capability
  - Highest integration density
  - Mass market driven
- Major MMIC Applications
  - Analog up to 77 GHz

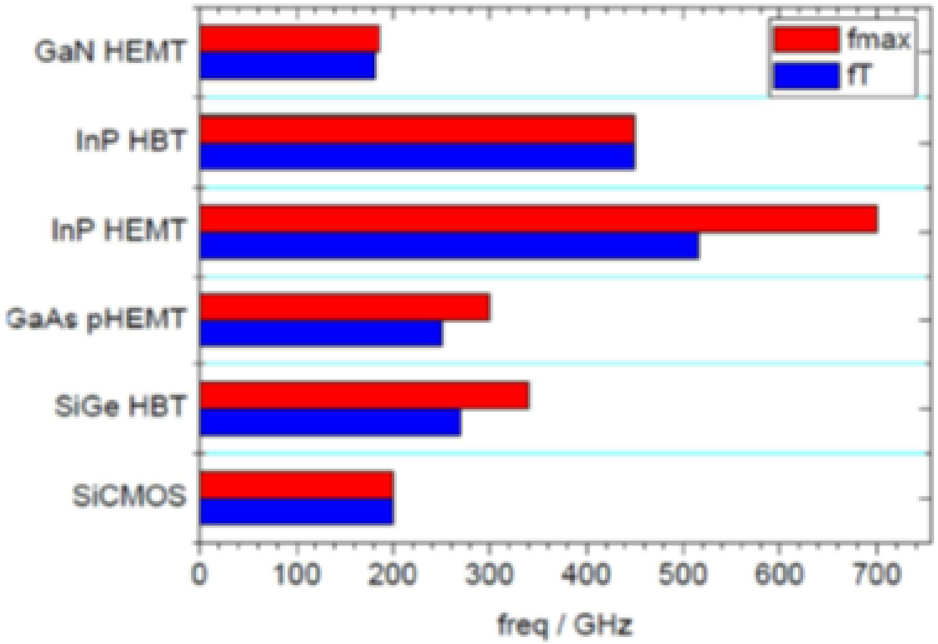


60 GHz Rx, 130nm CMOS ST Microelectronics
(Niknejad et.al CSICS 2007)

Dominating Types

Speed: Which semiconductor technology?

- f_T gain cut-off frequency is the mostly relevant in digital circuits and power amps
- f_{max} maximum oscillation frequency is mostly relevant in analog circuits (MMIC)
- Devices can be tailored for high f_{max} OR high f_T



Physical Power and Frequency Limitations of Semiconductor Devices

Relations: RF-Operating Parameters -- Semiconductor Features

$$2\pi \cdot f = \frac{1}{\tau} = v_s \cdot \frac{1}{\ell} = v_s \cdot \frac{E}{U} \quad \Rightarrow \quad U \cdot f \le \frac{v_s \cdot E_B}{2\pi}$$

analog for $I \cdot X_c \cdot f$

$$x_c = \frac{1}{\omega C};\; v_s = \frac{l}{\Delta t};\; C = \frac{Q}{U} = \frac{I \Delta t}{El}$$

$$\Rightarrow \quad P \cdot f^2 \le \frac{1}{X_c} \cdot \left(\frac{v_s \cdot E_B}{2\pi} \right)^2 = \text{constant!}$$

Similar for Power Gain $G \cdot f^2$

Limitation: Saturation Velocity v_s and Breakdown Field E_B

	Si	$Si_{1-x}Ge_x$ x = 0.12	SiC	Ge	GaAs	GaN
v_s [km/s]	60	78	200	60	100	250…270
E_B [MV/m]	20	54	220	10	30	330…380
$v_s \cdot E_B / 2\pi$ [V·GHz]	190	670	7000	95	480	≈15000

Schaltungen und Bausteine der HMT
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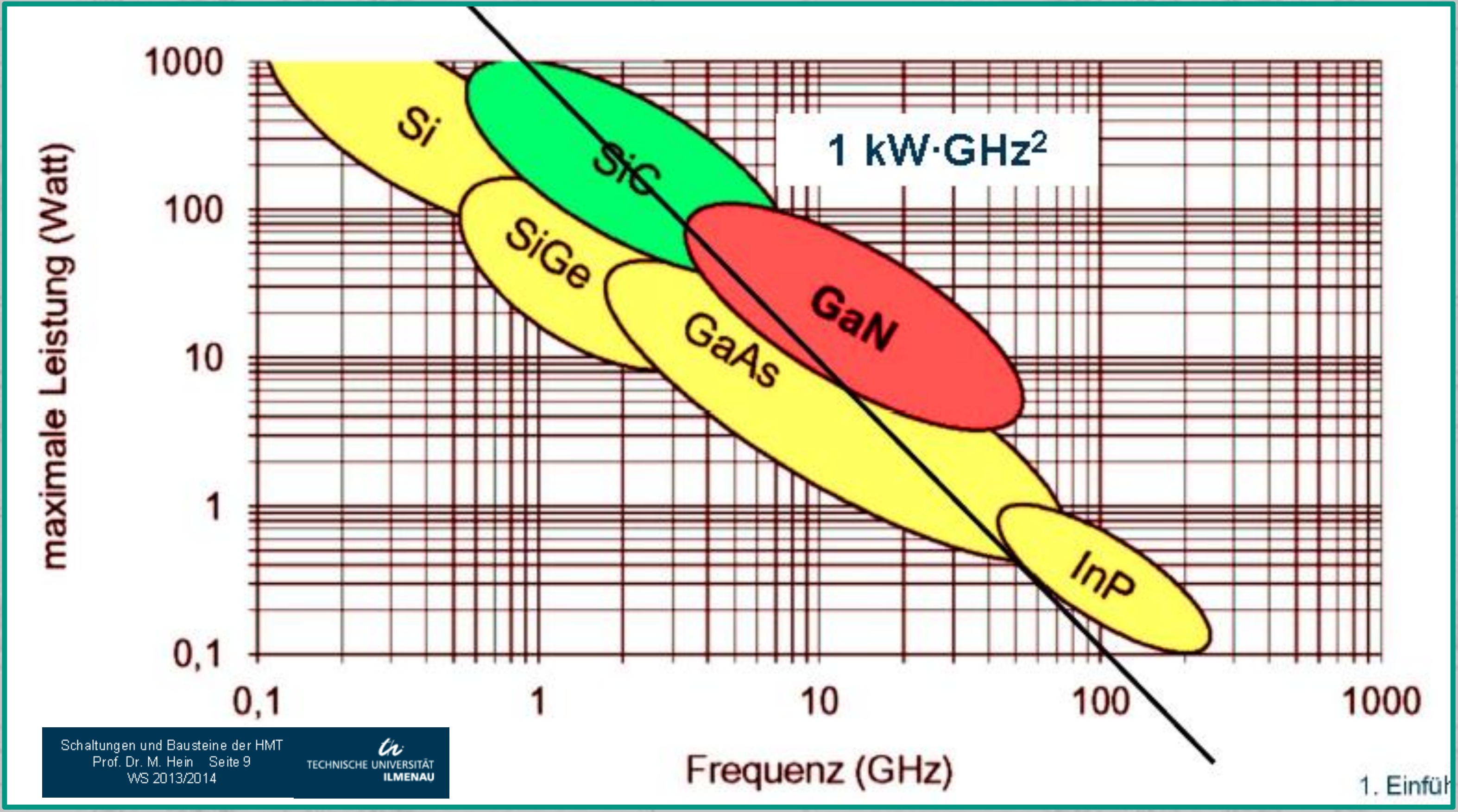
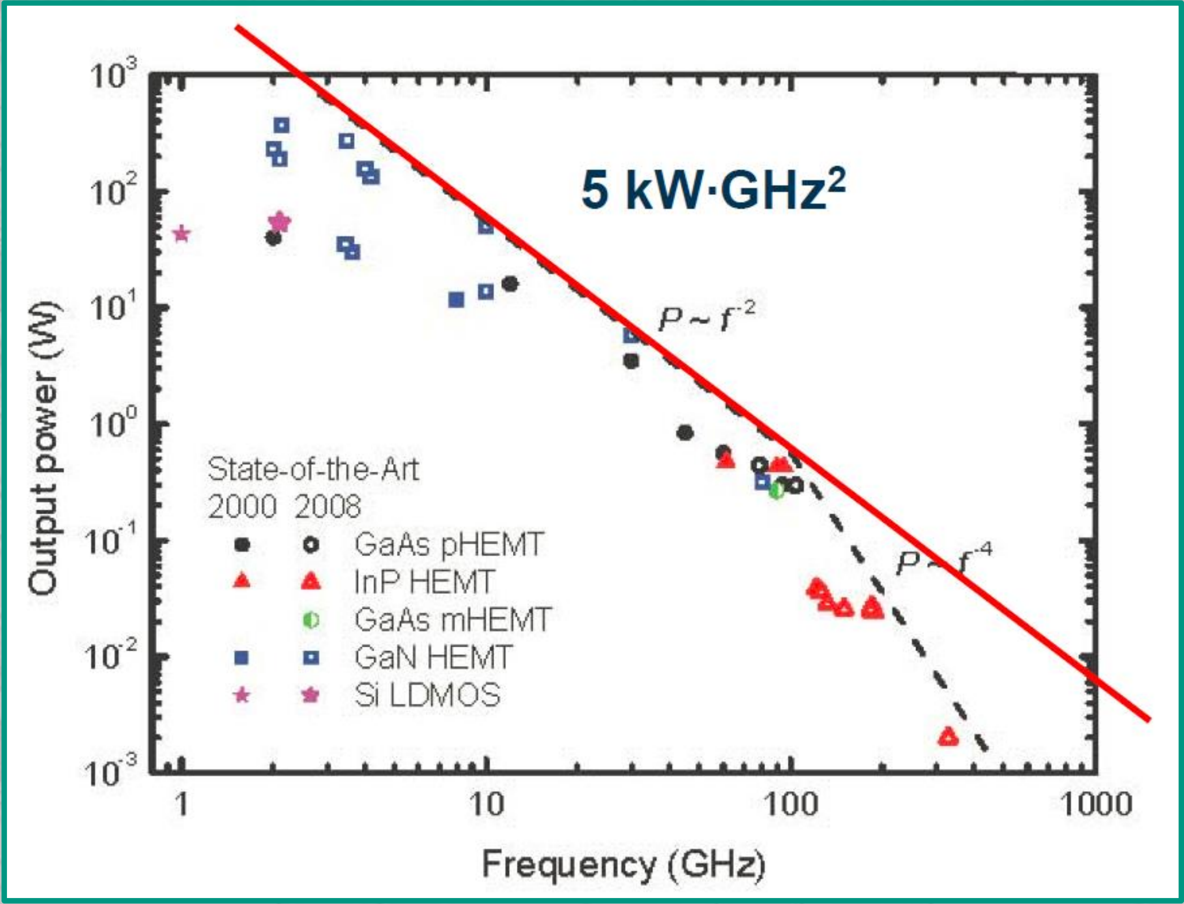
Technological Power and Frequency Boundaries



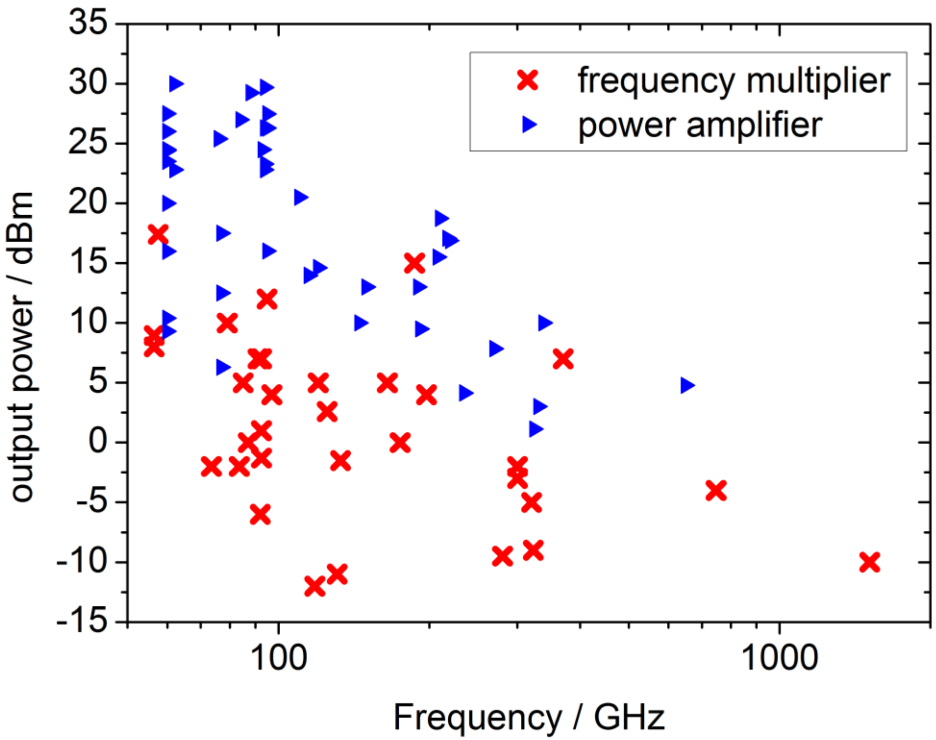
Pf^2-Product for RF Semiconductor Amplifier

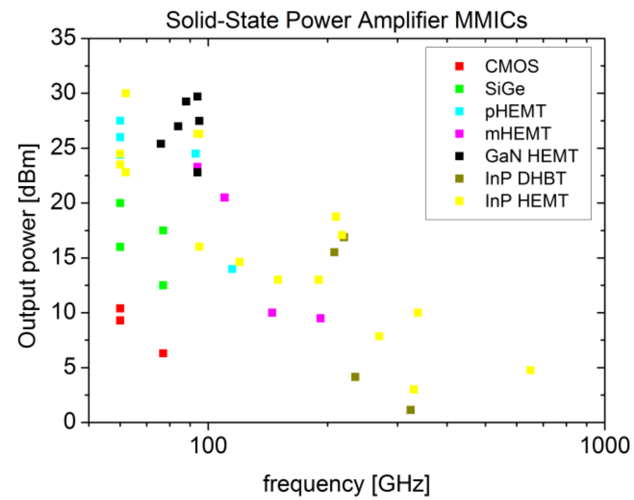


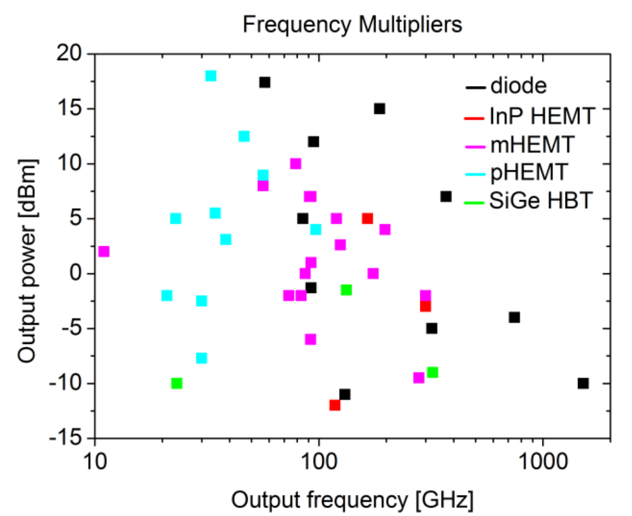
Source: M. Hein, *Schaltungen und Bausteine der HMT*, TU Ilmenau

1-10 GHz	: **Si LDMOS**, GaAs (pHEMT, HBT), **GaN HEMT**
10-100 GHz	: GaAs (pHEMT, mHEMT), InP und GaN HEMT
100-1000 GHz	**: InP HEMT**

Output Power for semiconductor Amplifier and Mixer







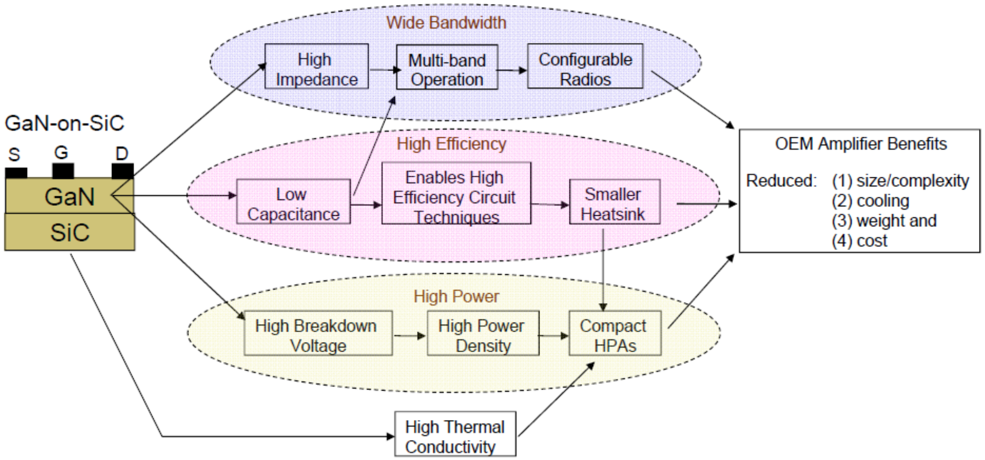
Source: Private Communication I. Kallfass, et. al., 2012

Comparison of III-V-Semiconductor

Semiconductor (Typical materials)		Silicon	Gallium Arsenide	Indium Phosphide	Silicon Carbide	Gallium Nitride
Characteristic	Unit					
Bandgap	eV	1.1	1.42	1.35	3.26	3.49
Electron mobility at 300 °K	cm^2/Vs	1500	8500	5400	700	1000-2000
Saturated electron velocity	$X10^7$ cm/s	1	1.3	1	2	2.5
Critical breakdown field	MV/cm	0.3	0.4	0.5	3	3.3
Thermal conductivity	W/cm°K	1.5	0.5	0.7	4.5	>1.5
Relative dielectric constant	ε_r	11.8	12.8	12.5	10	9

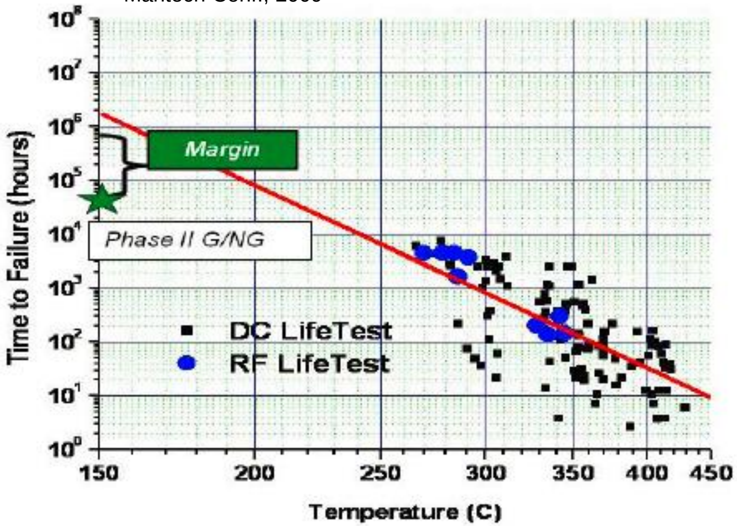
Characteristic of SiC und GaN:

- high breakdown voltage
- High current/power density
- Excellent thermal conductivity
- Low bulk resistance
- High live time



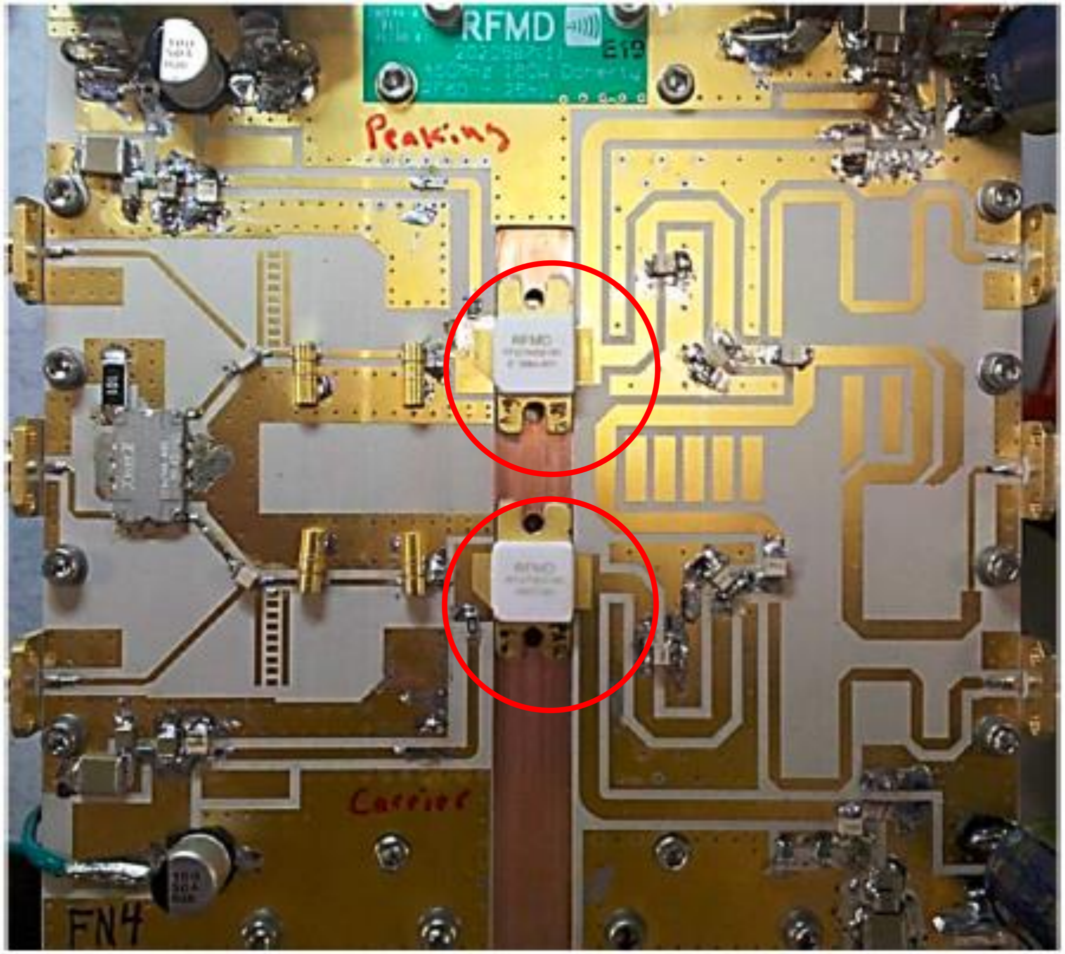
10x higher thermal conductivity for GaN-SiC compared to GaAs

M. Rosker, The DARPA Wide Band Gap Semiconductors for RF Applications (WBGS-RF) Program: Phase II Results, CS Mantech Conf., 2009



DARPA: Degradation eines TriQuint Hochleistungsverstärkers (MTTF of > 106 hours at a junction temperature of 150°C)

Amplifier for Base Station Application



180 W @450 MHz

- GaN FET
- air-cavity ceramic package
- Board size = 127 x 127 mm
- Taconic RF-60, 0.635 mm

For Comparison: Microwave Tubes

- Gyrotron
  - Main Application: Fusion (ECRH), Materials Processing
  - < 1 MW (CW), 10 - 300 GHz
- Magnetron
  - Radar, Industrial Applications
  - < 10 kW (CW), 0.6 - <60 GHz
- Klystron
  - Particle Accelerators
  - <1 MW (CW), 0.1 – 40 GHz
- Travelling Wave Tube
  - Space Applications
  - < 1.5 kW (CW), < 60 GHz


S-band klystrons, 45 MW peak, 20 kW average at 2998.5 MHz


Gyrotron, 2.2 MW peak at 170 GHz


Magnetron, 200 kW peak at 9 GHz

For Comparison: Typically Proportion of Energy Converter similar to MW-Power

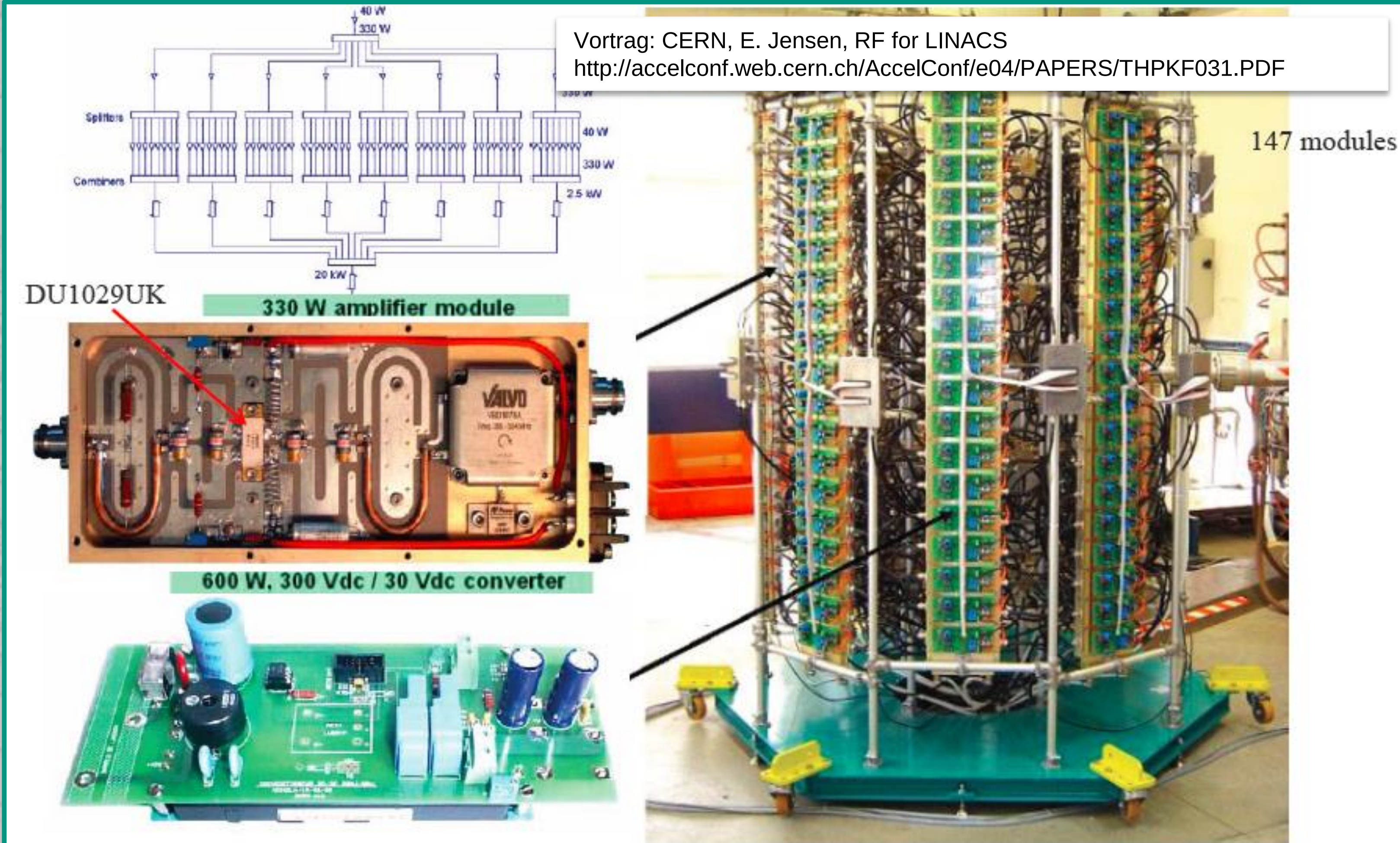
KIT
Karlsruher Institut für Technologie

1 MW, 700 MHz Klystron (CPI VKP-7952)

- Output Power: 1MW
- Acceleration Voltage: 95 kV (max.)
- Beam Current: 21 A (max.)
- Efficiency: 65 %
- The collector has designed for the complete power dissipation (~540kW).

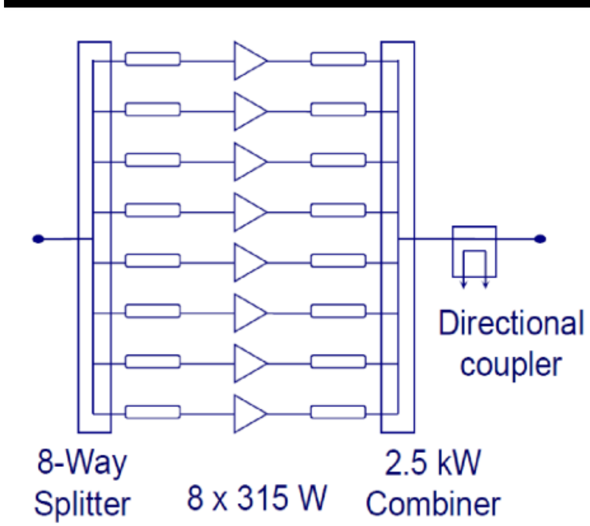
0.78 MW Combustion Engine

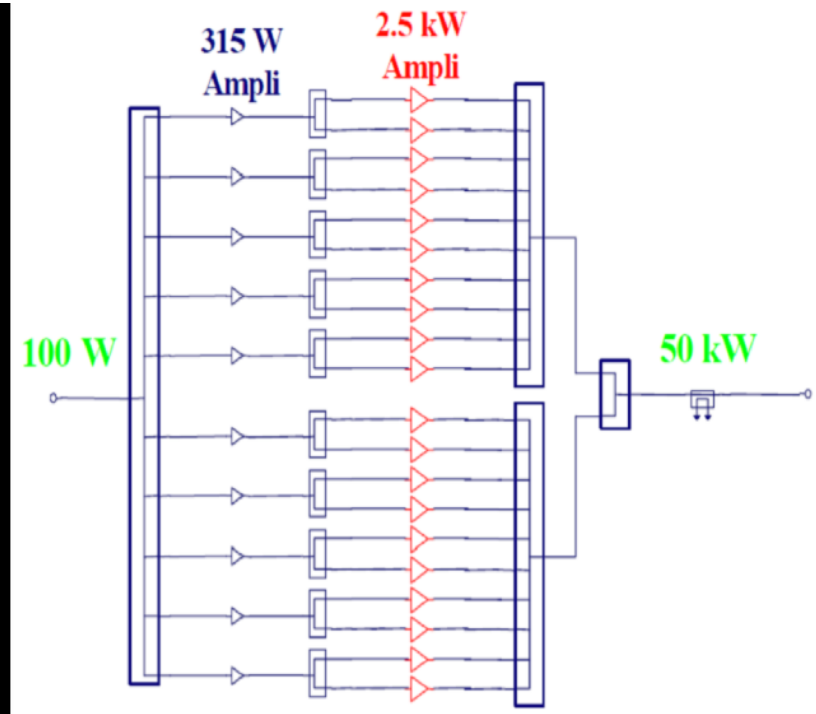
…, and again,
CAS Soleil Booster SSPA, 0.040 MW, 352 MHz

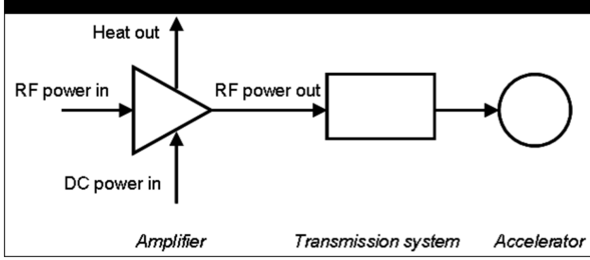


The mechanical dimensions of energy converter with similar output power and efficiency are comparable.

Semiconductor System for Particle Accelerators





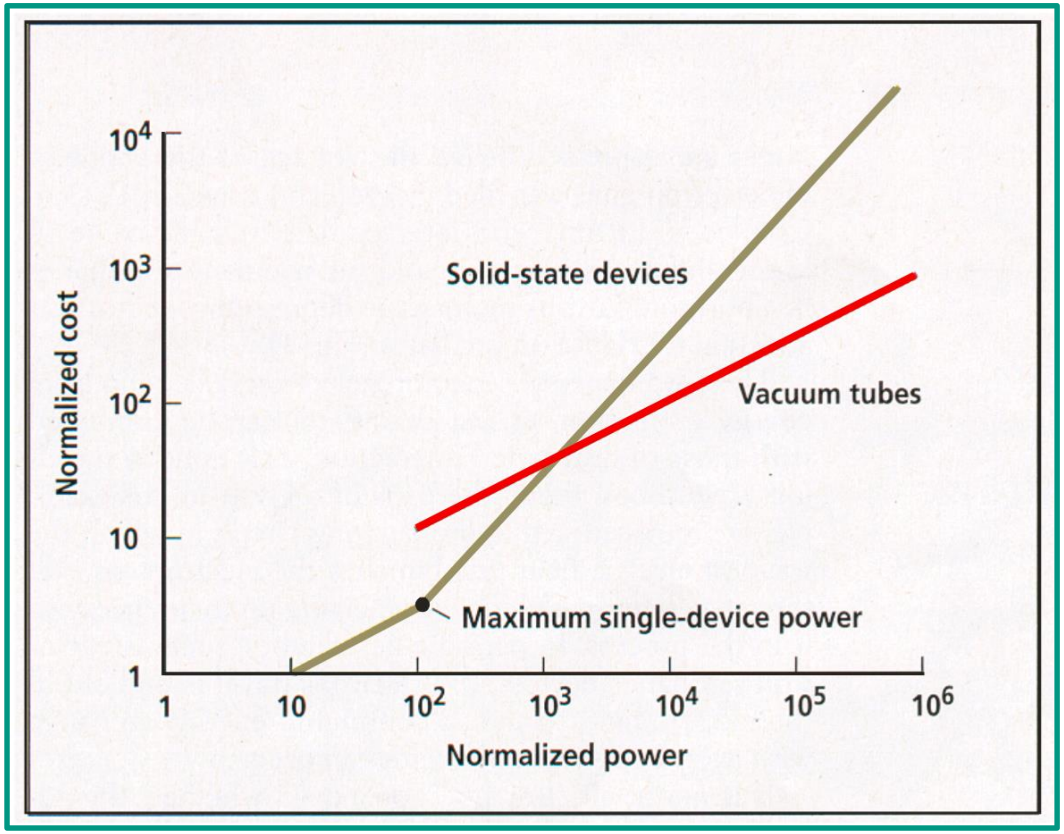


	LR 301[a]	TGF2023-20		TGF4240-SCC
Manufacturer	Polyfet	TriQuint		TriQuint
Material	Si LDMOS	GaN		GaAs
Frequency	350 MHz	3.0 GHz	14 GHz	8.5 GHz
Mean r.f. power	300 W	90 W	50 W	14 W
Operating voltage	28 V	30 V	30 V	8 V
Gain	13 dB	17 dB	5 dB	10 dB
Maximum junction temperature	200 °C	200 °C	200 °C	150 °C

a. Two transistors in push-pull.

Source: *R.G. Carter,* **RF power generation,** Engineering Department, Lancaster University, Lancaster LA1 4YR, U.K. and The Cockcroft Institute of Accelerator Science and Technology, Daresbury, UK

Costs for Single Sources vs. Power Addition



Quelle: R. S. Symons, Litton Electron Devices Division, 1998

- Costs of a single source increases with the root of the power, but
- Costs for power addition increase linearly!

→ Possible cost advantage for singe sources with higher power level

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Advantages/Disadvantages of the Power generation by vacuum electron devices

Advantage:

- Higher operating temperature = smaller cooling effort.
- Insensitive towards environmental influences like cosmic radiation and radioactivity.
- Insensitive against offset voltage and resistant against EMP.
- Higher power gain, higher dynamic bandwidth, constant parameter about a huge frequency range, very small and voltage constant inner capacities .
- Available for very high power (till the MW range at frequencies in the mmW-range).
- High „Peak“ – Power (ms-range).

Disadvantage:

- Complex DC–current supply with heating voltage (1,5 V till 40 V) and acceleration voltage above 1 kV till 100 kV
- High space requirement and bordered integration possibilities.
- Delayed operating state due to the cathode heating time
- High production costs and low quantities by complex production steps (small mechanical tolerances)
- Sensitivity against mechanical demands (microphonics, breakage of glass, inner damages)
- Changes due to aging of the electronic values and smaller life time
- No complementary types analoge to p-channel/n-channel-MOSFETs respectively PNP/NPN bipolar junction trasnistor is available

Categorization of the demanded power

High Power Microwave Sources

High pulse power

Narrow band (coherent) power generation

1 GHz … 100 GHz

10 ns … 100 ns

Monoenergetic Electron Beam

Ultra-broadband (UWB) Power generation

0,01 GHz … 10 GHz

High Voltage Pulses

High CW Power

equivalent in the type of power generation

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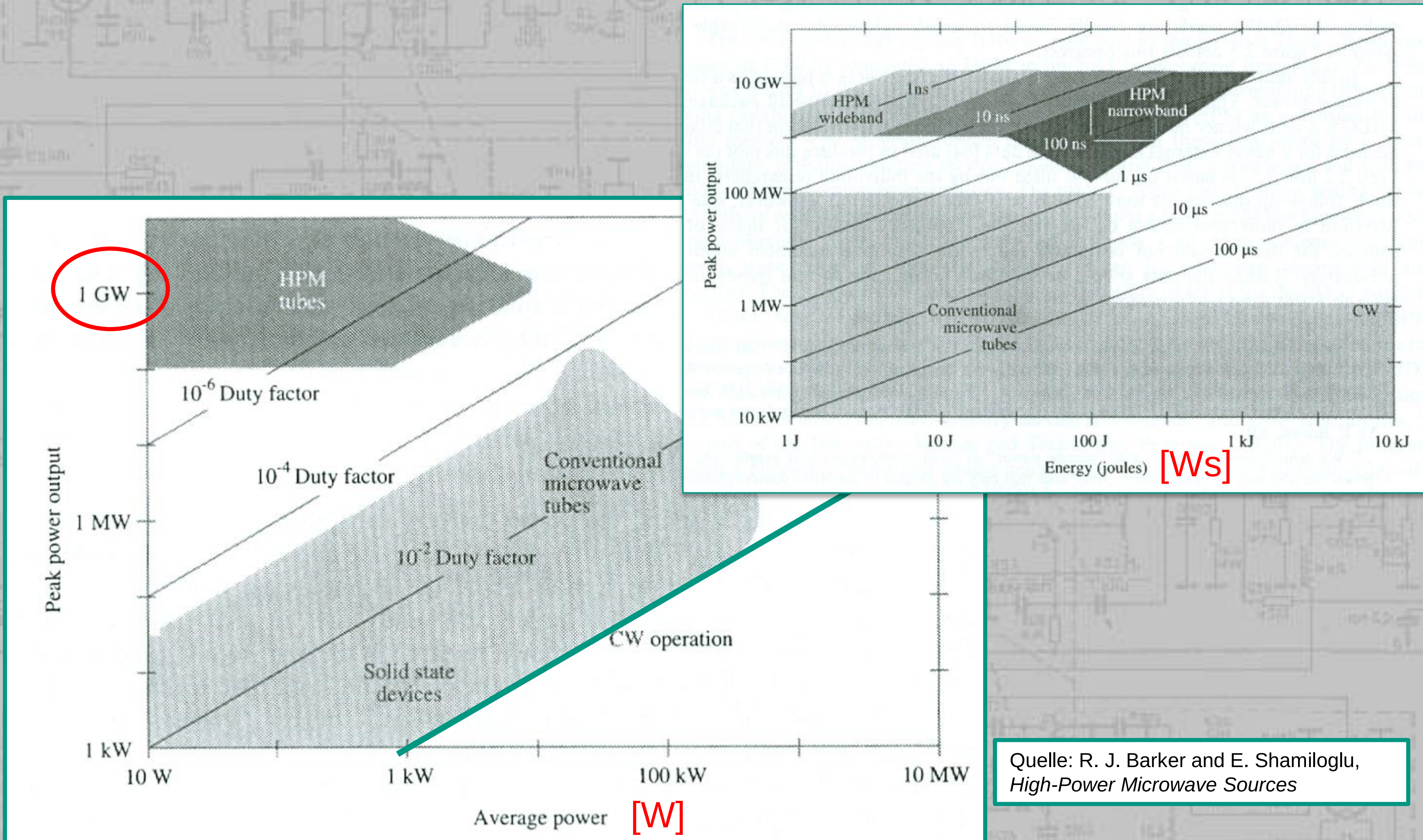
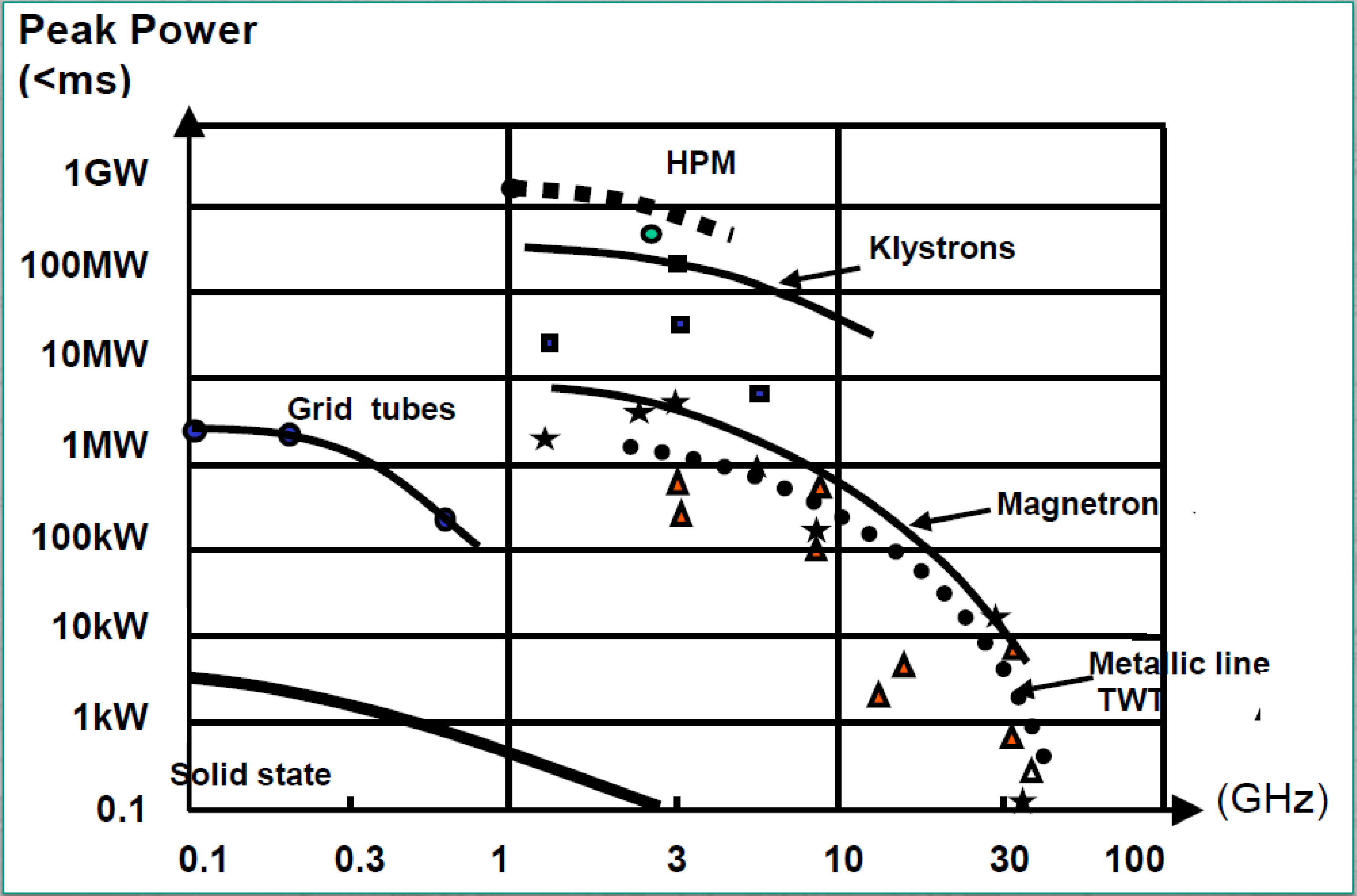
High Pulse Power in the Microwave Technique

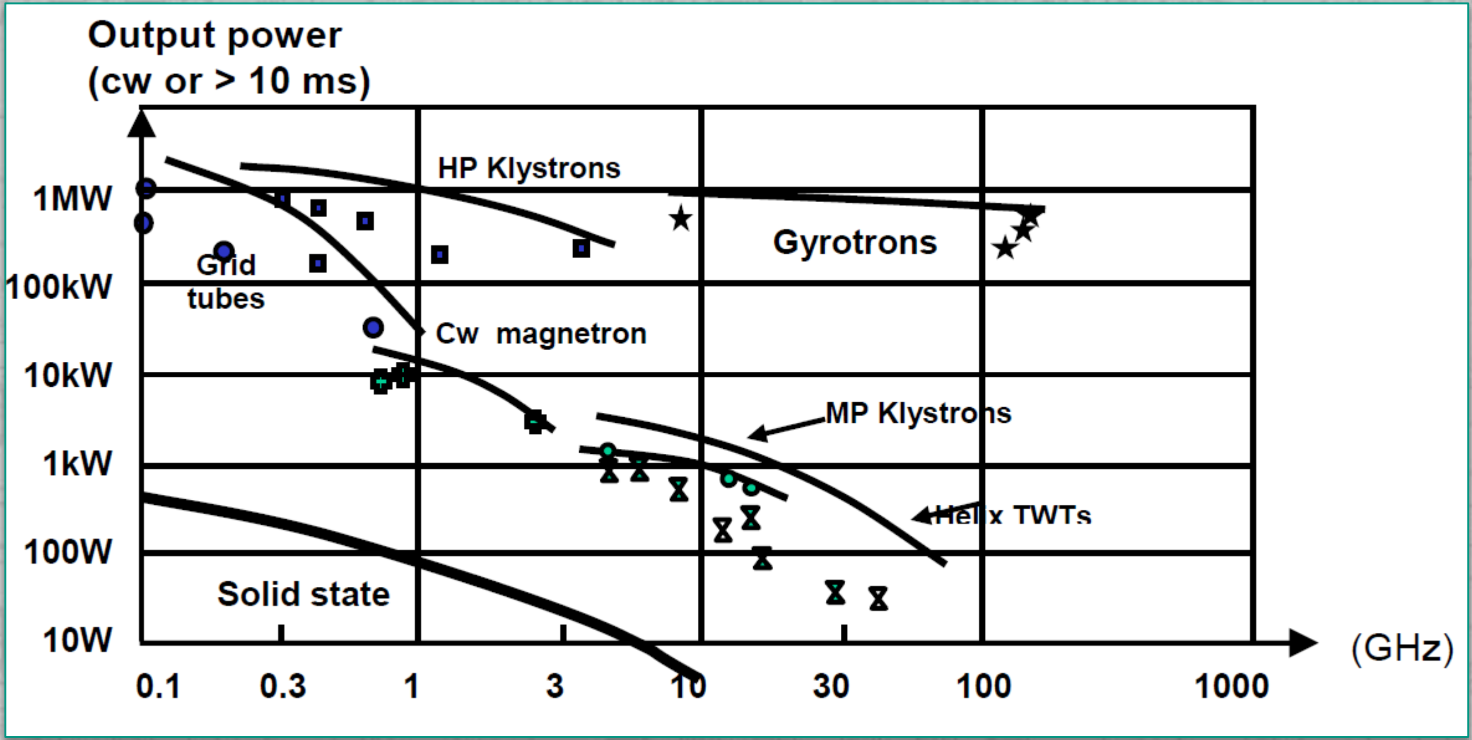


Quelle: R. J. Barker and E. Shamiloglu, *High-Power Microwave Sources*

…, classified to the microwave sources



High CW power in the Microwave Technique



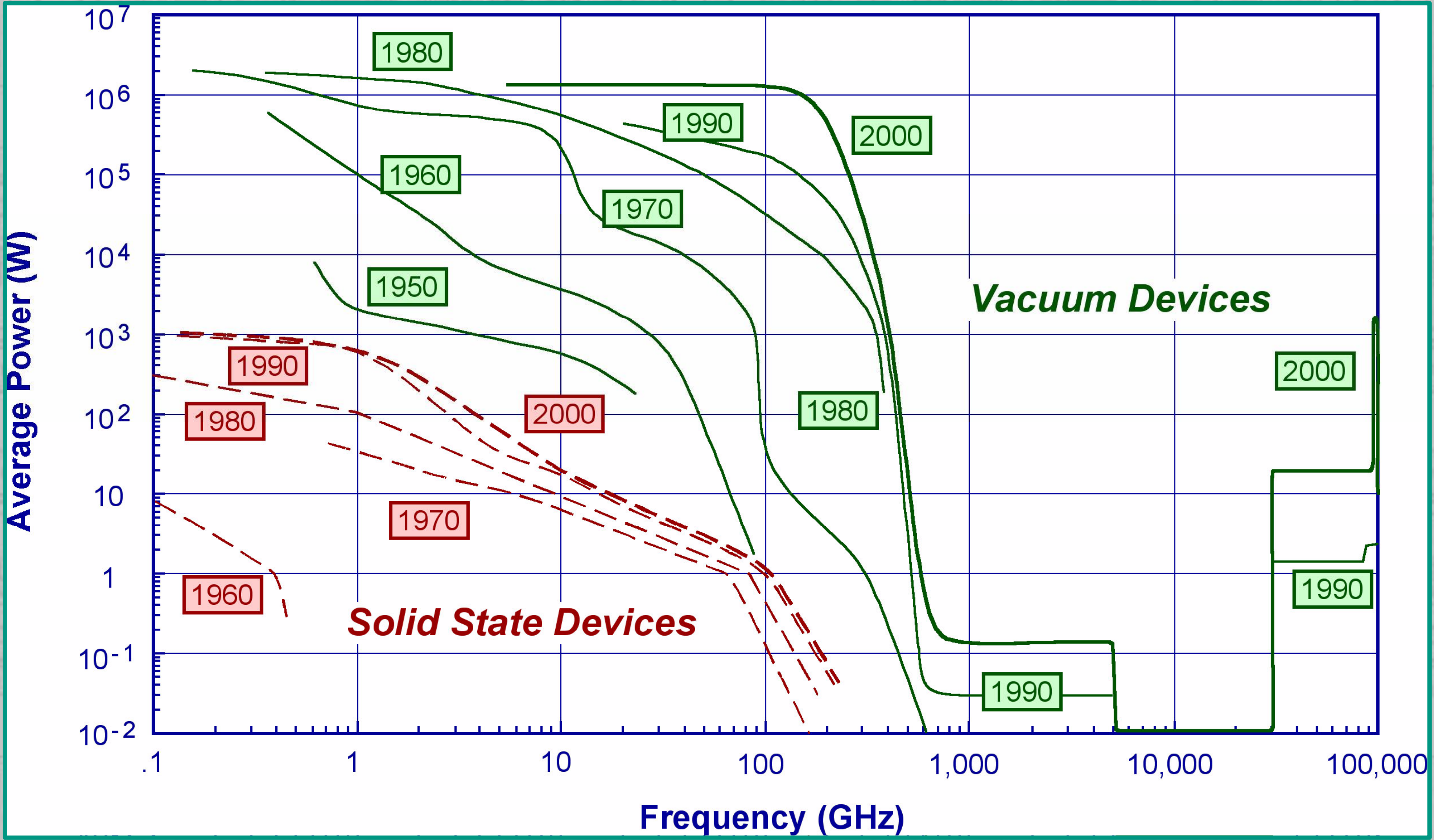
For **electron vacuum devices** applies:

Maximum pulse power >> Maximum CW power

For **semiconductor sources** applies:

Maximum pulse power = Maximum CW power

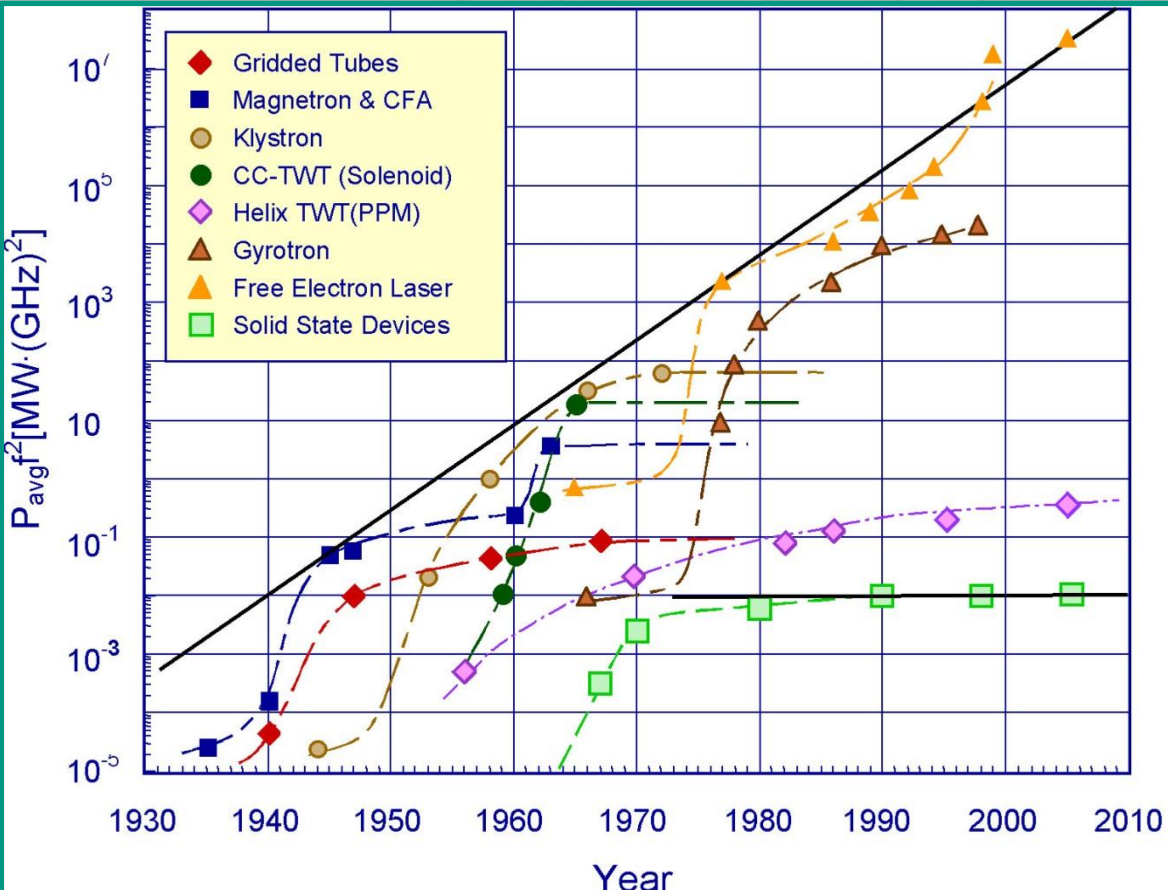
The historical Development of the output power

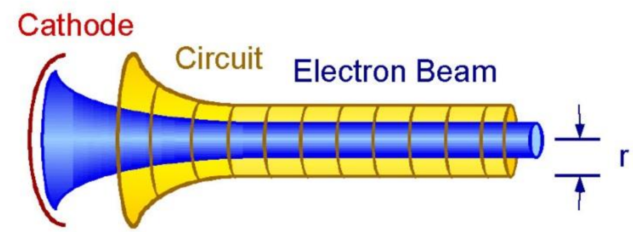


Quelle: B. Levush, et al, „Vacuum Electronics: Status and Trends", Aerospace and Electronic Systems Magazine IEEE (2007)

The chronological Development of the Pf² for electron vacuum devices.

The „Power-Frequency-Product“ Pf² for electron vacuum tubes doubles every 2 years.





- Pf^2 - Power Density
- Measure of Ability to Generate “RF” Power
- $Pf^2 \propto \delta^2\beta E_m^2$ where
  - $\delta = r/\lambda$ and
  - β = carrier velocity
  - E_m = electric field in space charge region

Source: B. Levush, et al, „Vacuum Electronics: Status and Trends“, Aerospace and Electronic Systems Magazine IEEE (2007)