Karlsruhe Institute of Technology

Hoch- und Höchstfrequenzhalbleiterschaltungen (HHHS) Millimetre-wave monolithic integrated circuit design

Winter term 2013/2014

lecture overview

INSTITUT FÜR HOCHFREQUENZTECHNIK UND ELEKTRONIK

overview

- Millimetre-wave monolithic integrated circuit (MMIC)
  - a definition
  - features of an MMIC
- reasons for operating in the millimetre-wave regime
  - frequencies, advantages
- mmW and MMIC technologies
- mmW system set-up
  - analogue front-end building blocks
- application examples
- prize considerations

MMIC: a definition

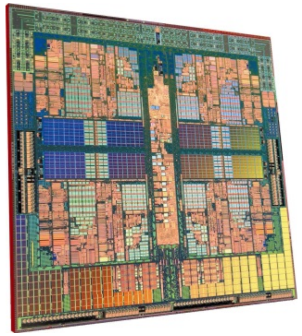
- trad.: monolithic microwave integrated circuit (3...30 GHz)
- at mm-wave frequencies: millimetre-wave monolithic integrated circuit (30... 300 GHz)
- ”monolithic” = from Greek “monólithos” = single stone

- “A monolithic microwave integrated circuit is an active or passive microwave circuit formed in situ on a semiconductor substrate by a combination of deposition techniques including diffusion, evaporation, epitaxy, and other means.” Robert A. Pucel

- MMIC versus hybrid mm-wave technologies
  - cost reduction by batch processing
  - higher reliability and improved reproducibility
  - size and weight reduction
  - circuit design flexibility and multifunction performance
  - multi-octave operation

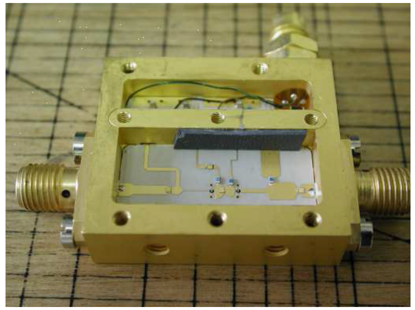
MMIC: a definition by comparison

- **IC** integrated circuit
  - term used today for digital circuits
  - 45/65/... nm Si-CMOS
  - billions of transistors
  - many levels of metal interconnect layers (visible on surface)



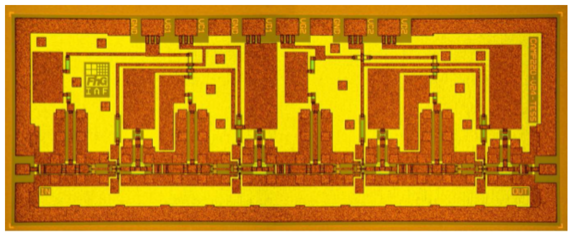
AMD Phenom (2007)
65 nm SOI CMOS
image: wikipedia

- **MIC** micro/millimetre-wave integrated circuit
  - hybrid combination of active and passive components on a substrate (circuit board)
  - alumina Al2O3
  - LTCC (low-temperature cofired ceramics)
  - soft-board, …



4-8 GHz cryo-LNA MIC

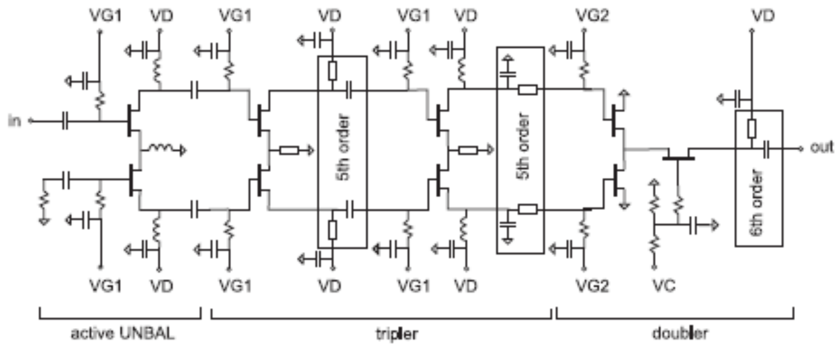
- **MMIC** micro/millimetre-wave integrated circuit
  - all circuit components on a single chip
  - S-MMIC: sub-millimetre-wave (>300 GHz) operation

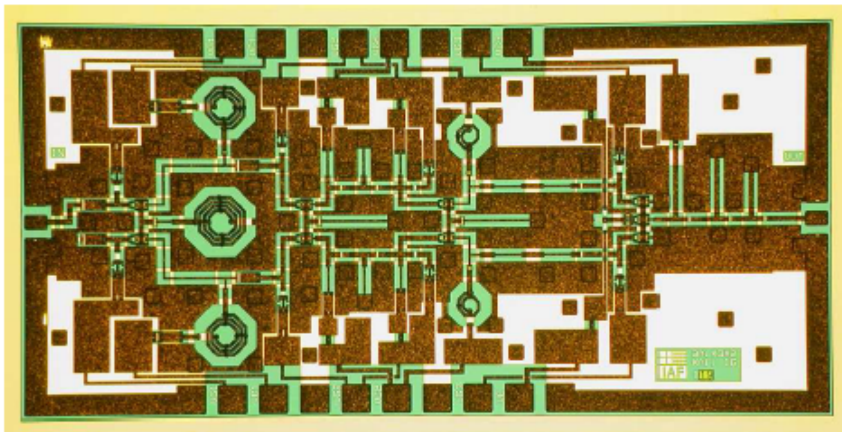


220 GHz LNA, Fraunhofer IAF

The “classic” MMIC

- features
  - III-V-based (GaAs, InP, GaN)
  - low integration density / large chip size
  - extensive use of reactive elements (matching, coupling, biasing...)
  - inter-stage matching
  - passives as distributed elements (transmission lines)
  - few levels (typically two) of metal interconnect layers

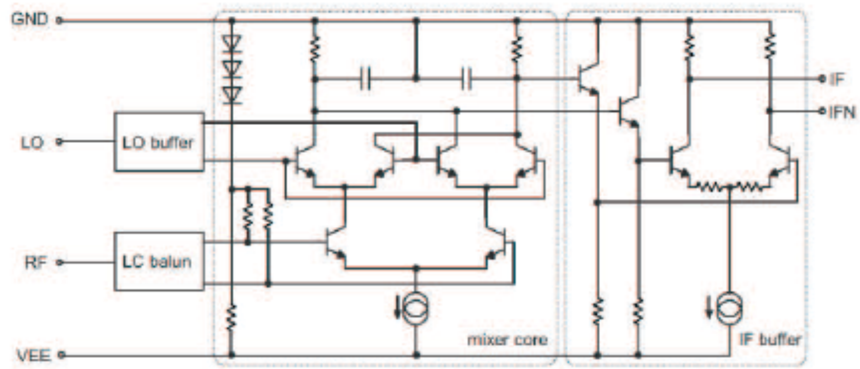


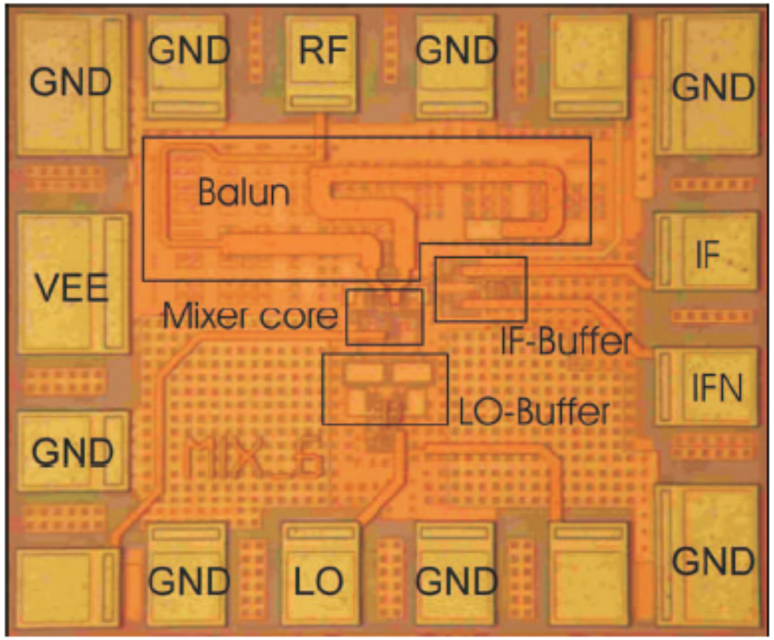


1 x 4 mm2

The “new” MMIC

- features
  - Si-based (SiGe HBT, Si CMOS)
  - high integration density / small chip size
  - limited use of reactive elements (transmission lines)
  - often differential topologies
  - in highly compact circuits (e.g. Gilbert cells), use of active impedance transformers

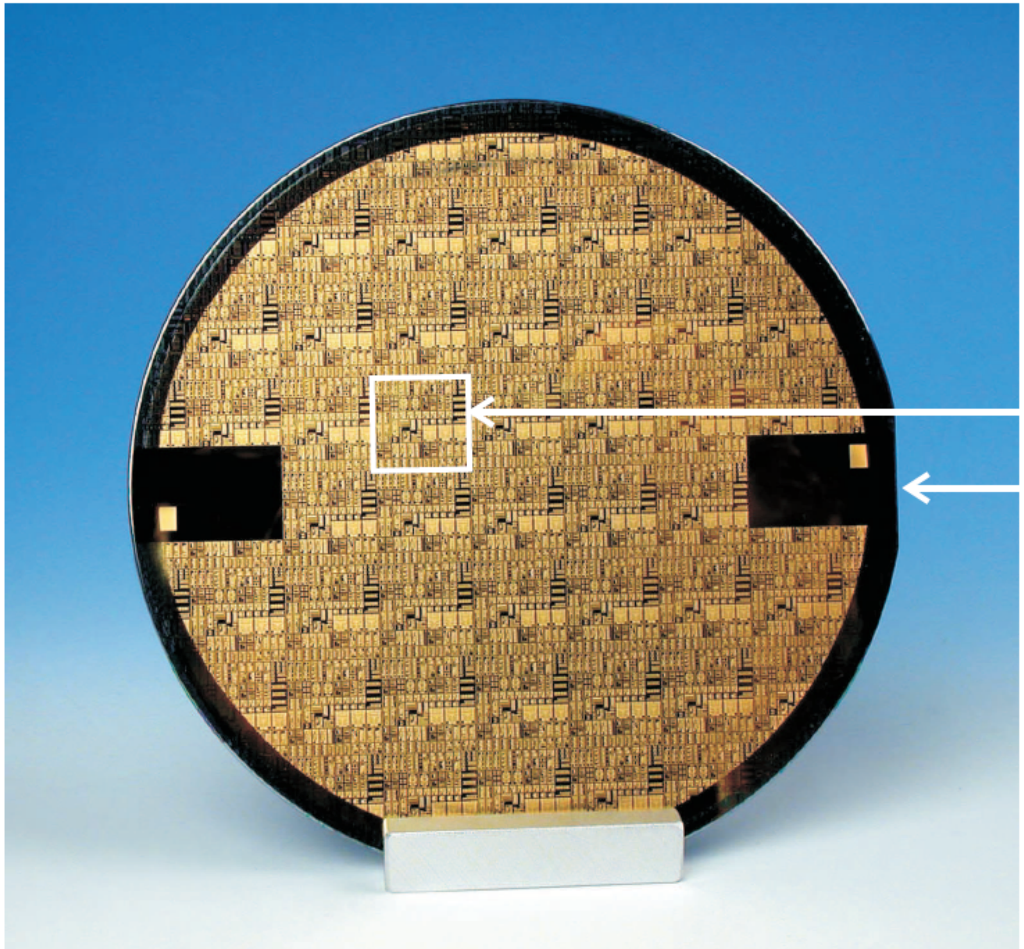




Institut für Hochfrequenztechnik
und Elektronik

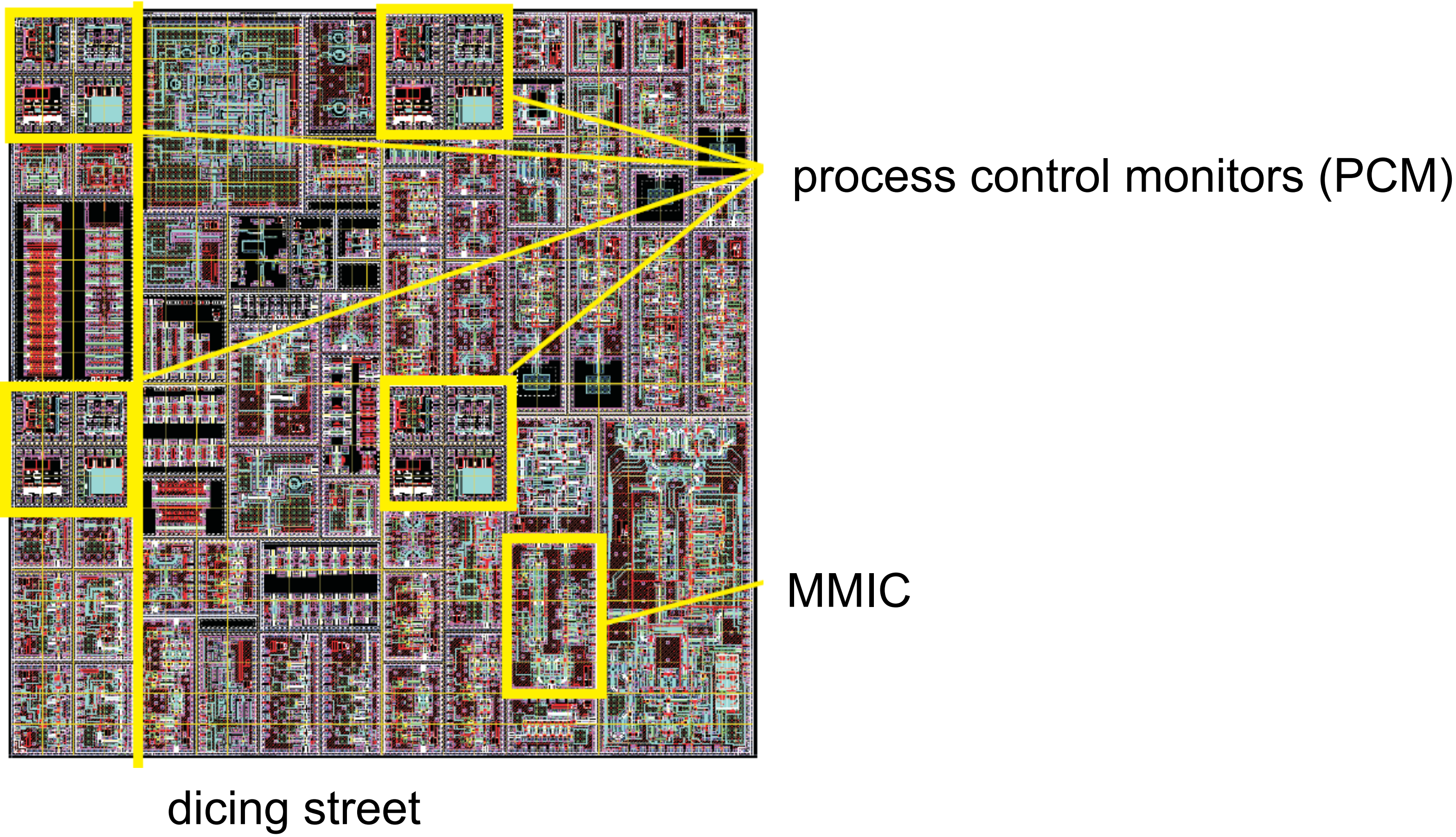
processed wafer

- 4” GaAs wafer



mask layout

- “pizza” mask
- e.g. 1.2 x 1.2 mm2



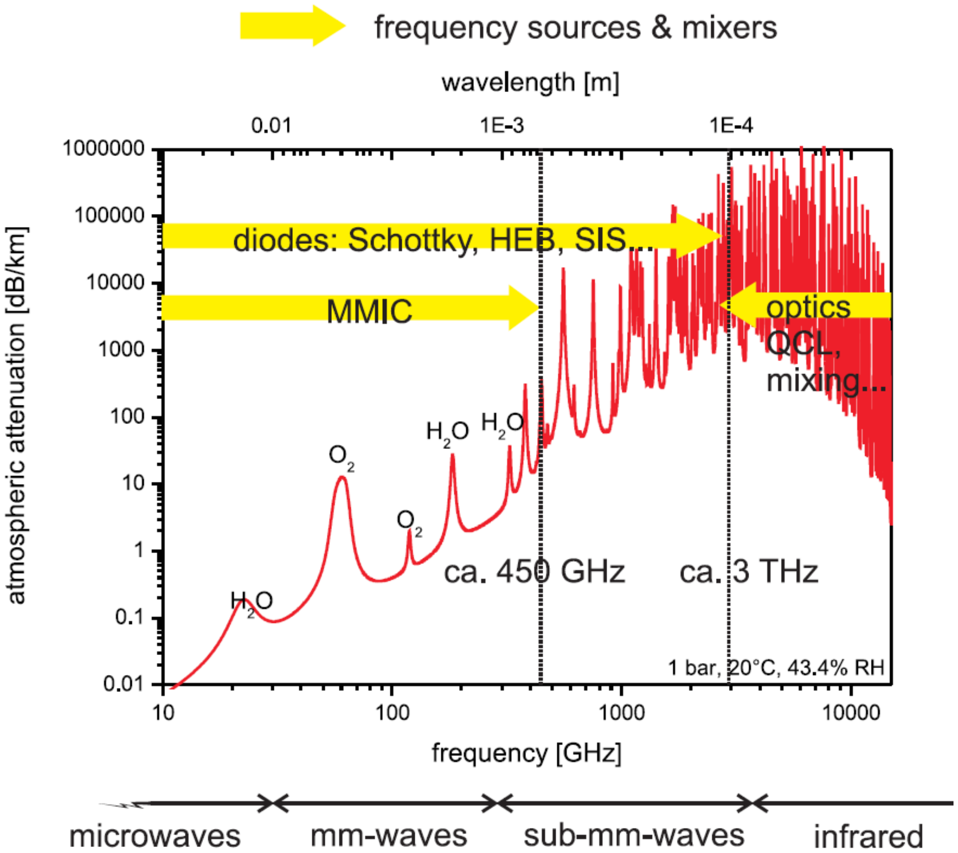
overview

- Millimetre-wave monolithic integrated circuit (MMIC)
  - a definition
  - features of an MMIC
- reasons for operating in the millimetre-wave regime
  - frequencies, advantages
- mmW and MMIC technologies
- mmW system set-up
  - analogue front-end building blocks
- application examples
- prize considerations

electromagnetic spectrum: the "THz gap"

Karlsruhe Institute of Technology

- microwave
  - 3 - 30 GHz
  - 10 - 1 cm free-space wavelength
- millimetre-wave
  - 30 - 300 GHz
  - 10 - 1 mm free-space wavelength
- sub-millimetre-wave
  - new term
  - MMICs operating beyond 300 GHz
- "THz"
  - loosely used in the literature
  - here: 0.1 - 10 THz
- infrared
  - Near-infrared (NIR): 0.75-1.4 µm
  - Short-wavelength infrared (SWIR): 1.4-3 µm
  - Mid-wavelength infrared (MWIR) also called intermediate infrared (IIR): 3-8 µm
  - Long-wavelength infrared (LWIR): 8–15 µm
  - Far infrared (FIR): 15-1,000 µm



THz technologies

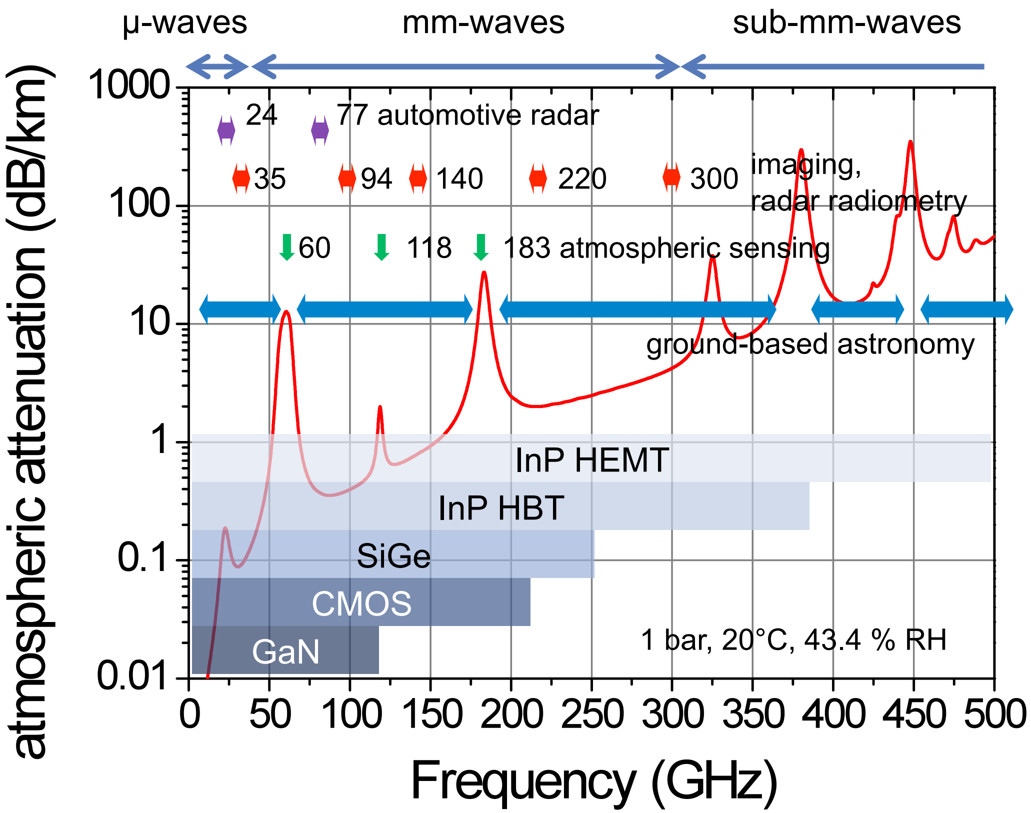
- advantages and disadvantages

	Optics	Cryogenic diodes (HEB, SIS)	Schottky diodes	MMIC
THz operation (0.1 – 1 THz)	feasible	feasible	feasible	limited
Mass manufacturability (batch processing, packaging, testing, …)	feasible	feasible	impossible	feasible
ease of deployment (size, weight, temp. stabilisation, …)	limited	impossible	feasible	feasible
multi-functional integration (generation, amplification, conversion, …)	impossible	impossible	impossible	feasible
miniaturisation (module form factor, multi-channel, …)	feasible	feasible	impossible	feasible

Institut für Hochfrequenztechnik und Elektronik

EM spectrum: frequencies and applications

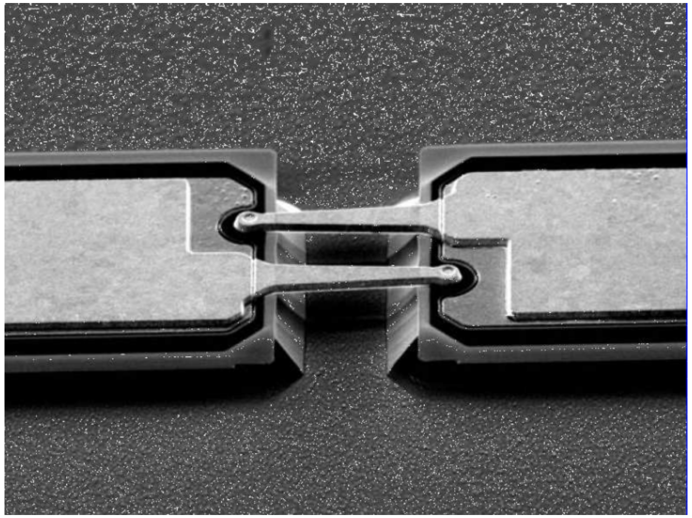
- spectroscopy
  - detect and monitor molecule absorption frequencies in mm-wave region
  - meteorology, atmospheric sensing, medical...
- mm-wave ranging and imaging
  - non-ionizing radiation penetrates clothing, adverse weather, packaging material
  - radar, safety & security, concealed weapon detection, avionics (landing aid, runway control)...



- higher frequencies = larger absolute bandwidths
  - high data rate communication systems
  - high geometrical resolution in radar

Schottky diodes: passive nonlinear circuits

- features
  - the classic millimetre-wave technology
  - dedicated processes not compatible with transistor technologies
- major applications
  - frequency multipliers and mixers beyond 100GHz
  - to-date up to >3 THz



Anti-parallel Schottky diodes
(Rutherford Appleton Lab, UK)

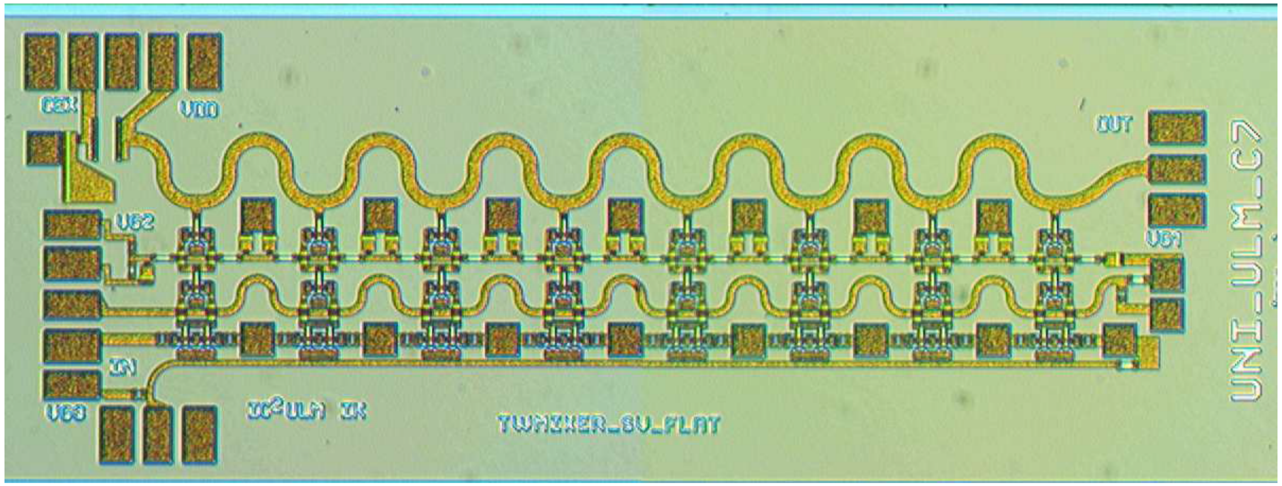
semiconductor technologies

- HEMT: high electron mobility transistor
- (D-)HBT: (double) hetero-structure bipolar transistor
- CMOS: complementary metal-oxide-semiconductor

	field effect transistor (FET)	bipolar junction transistor (BJT)
III-V-based	GaAs (pseudomorphic) HEMT InP (pseudomorphic) HEMT GaAs metamorphic HEMT	GaAs HBT InP (D-)HBT
Si-based	(RF-) CMOS	SiGe HBT

GaAs pHEMT

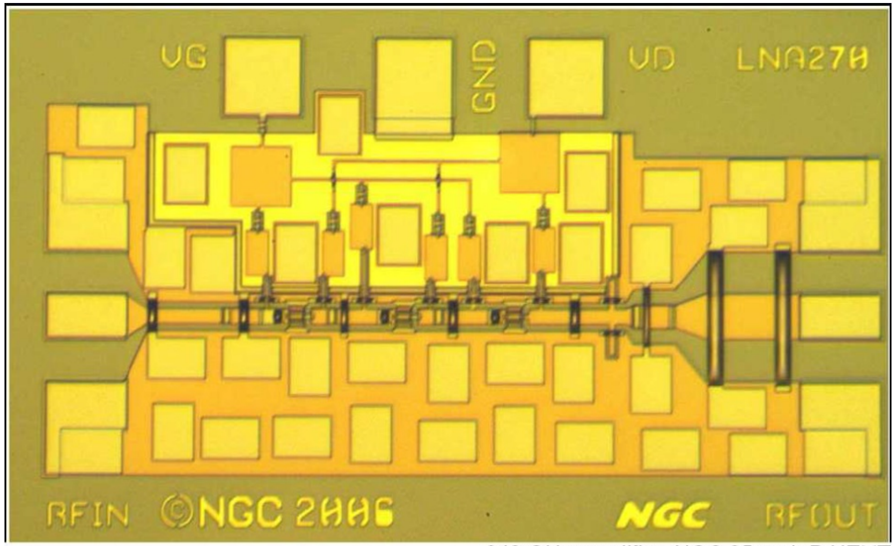
- features
  - the “classic” HEMT technology
  - many foundries worldwide
  - typically 4-6 inch wafers
  - major MMIC applications
  - analogue frontends (incl. LNA, mixer, PA) up to >100GHz
  - automotive + military radar
  - communication



150nm GaAs pHEMT travelling-wave mixer

InP HEMT

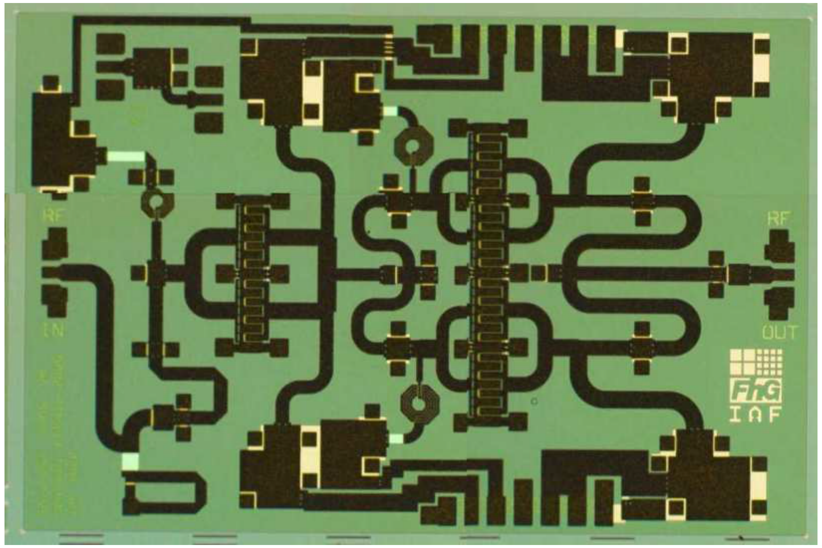
- features
  - (+) highest MMIC performance to-date
  - (-) InP substrate: brittle, max. 4”, costly
- major MMIC applications
  - ultra low-noise amplifiers
  - analogue frontends beyond 100GHz
  - radio-astronomy, mm-wave imaging
- metamorphic HEMT
  - InP HEMT on GaAs substrate
  - combine InP performance and advantageous GaAs substrates (prize, size, handling)



340 GHz amplifier, NGC 35nm InP HEMT

GaN HEMT

- features
  - high breakdown voltage
  - high speed
  - on 4” SiC wafers
- major MMIC applications
  - high efficiency and broadband power amplifiers up to Ka-band
  - base stations
  - radar

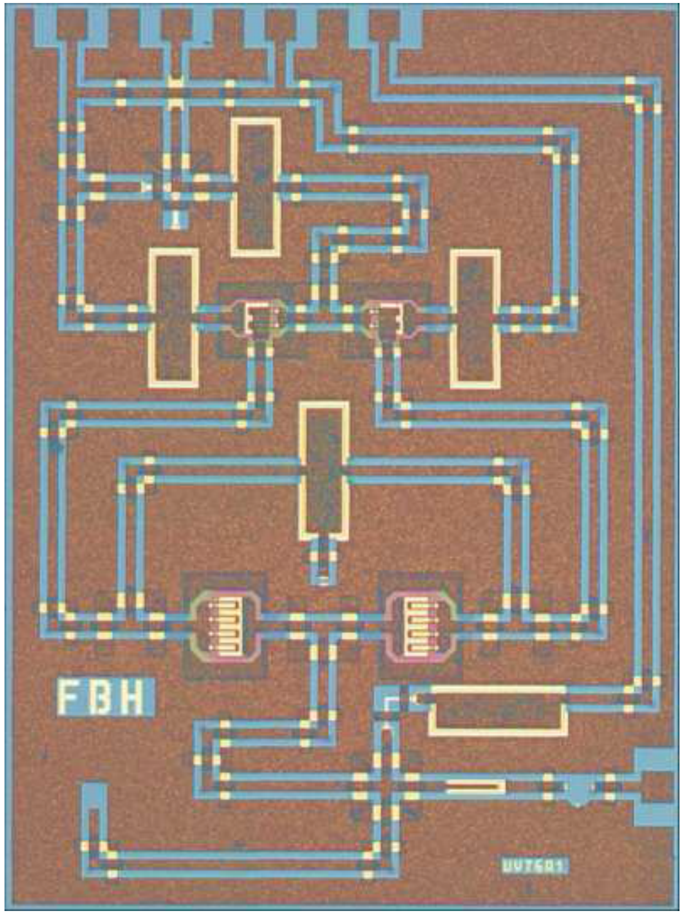


GaN X-band (10 GHz) power amplifier

Institut für Hochfrequenztechnik und Elektronik

GaAs HBT

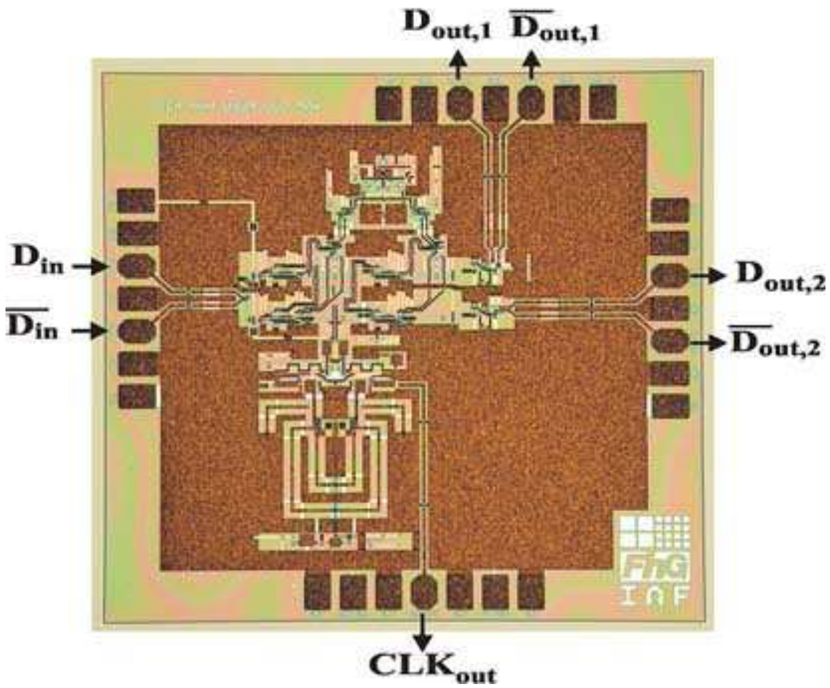
- features
  - high breakdown voltage
- major MMIC applications
  - power amplifiers
  - low phase-noise frequency sources (VCO)



76 GHz VCO, GaAs HBT FBH Berlin

InP (D)HBT

- features
  - high breakdown voltage
  - OEIC (opto-electronic integrated circuit): integrate with photodiode...
- major MMIC applications
  - mixed-signal circuits
  - optical communication systems (100 Gbit ethernet)
  - fast ADC/DAC

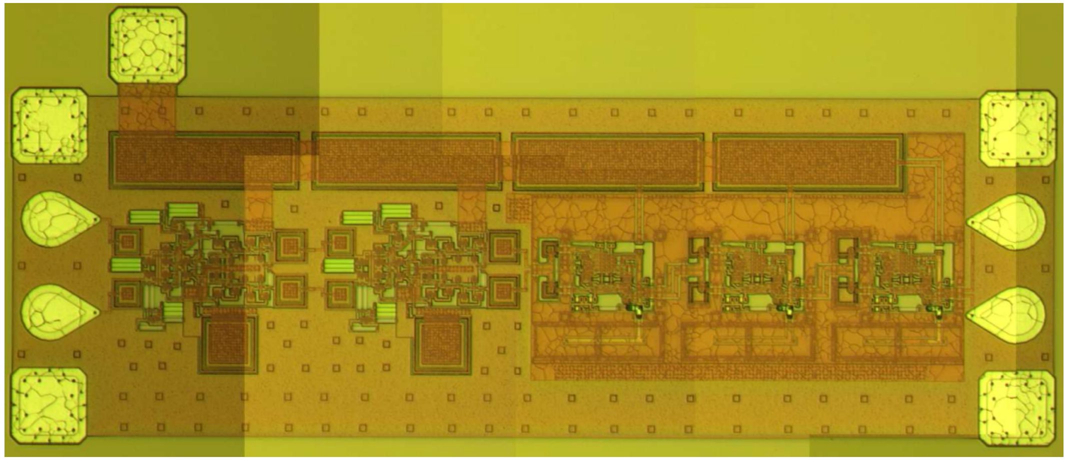


InP DHBT 80Gbps clock and data recovery

Institut für Hochfrequenztechnik
und Elektronik

SiGe HBT

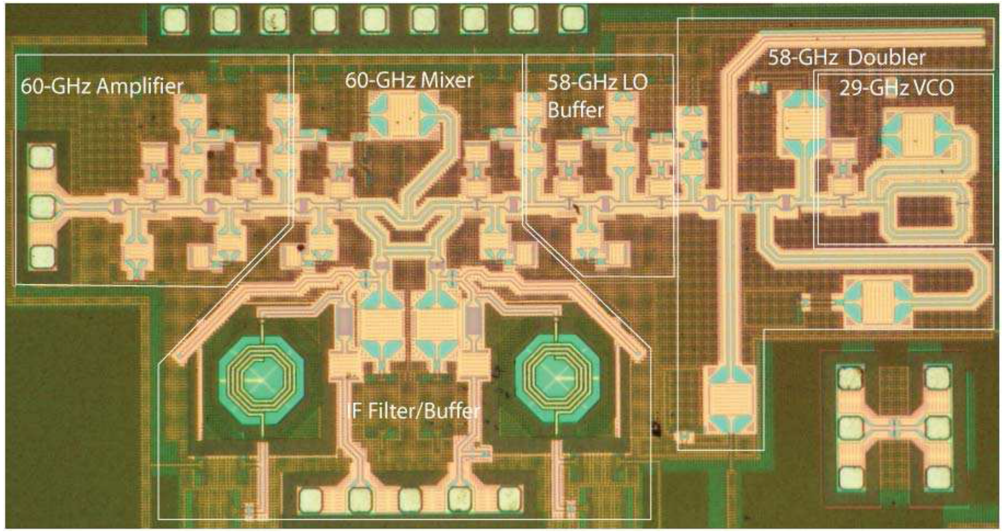
- features
  - high frequency capability
  - comes in BiCMOS processes
  - high integration density
- major MMIC applications
  - analog up to 77GHz
  - mixed signal: e.g. fast ADC/DAC



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

(RF-) CMOS

- features
  - fast increasing high frequency capability
  - highest integration density
  - mass market driven
  - RF-CMOS for higher breakdown voltages
  - 8”-12” wafers
- major MMIC applications
  - analogue up to 77GHz
- mixed signal: e.g. fast ADC/DAC

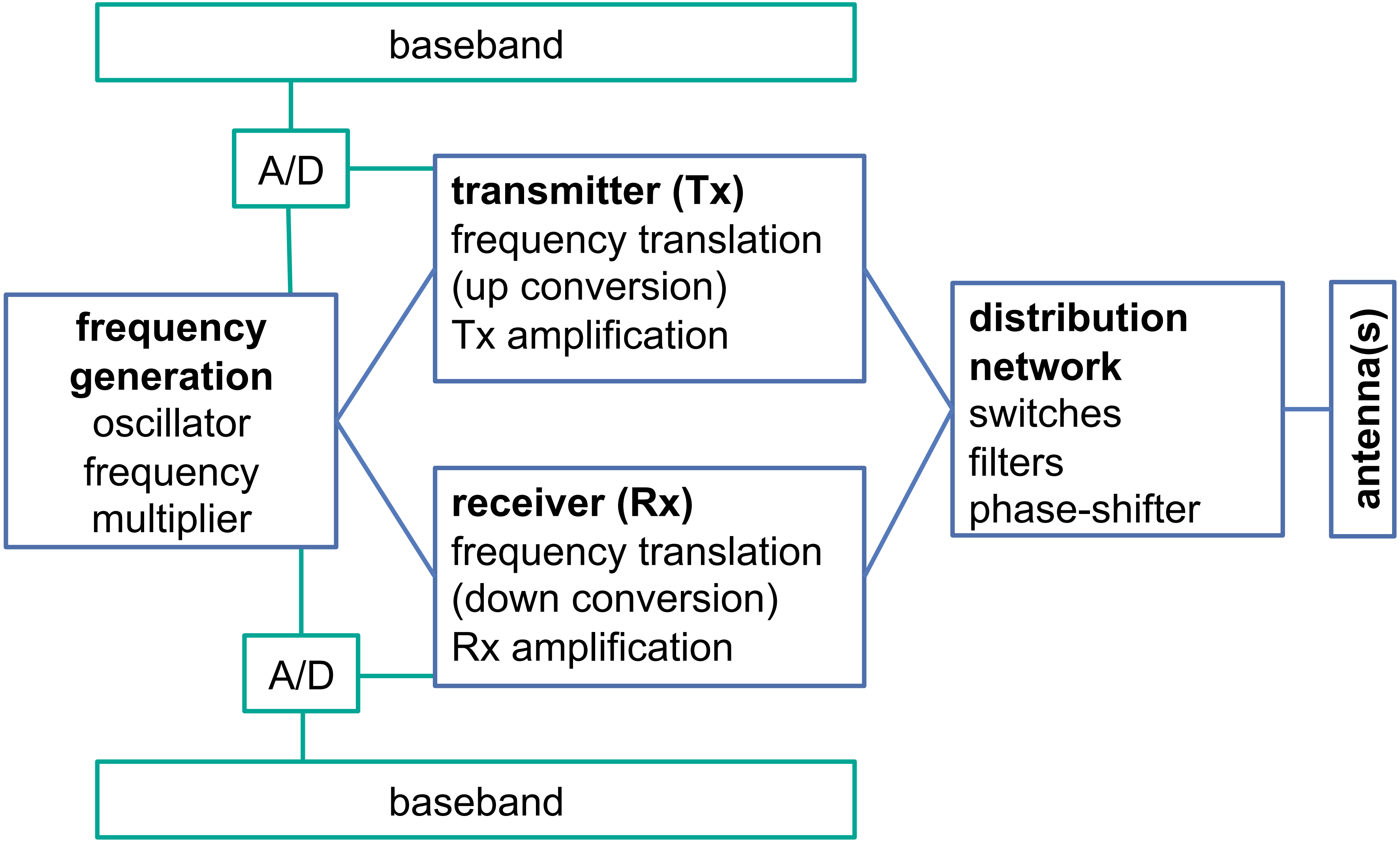


60 GHz Rx, 130nm CMOS ST Microelectronics
(Niknejad et.al CSICS 2007)

overview

- Millimetre-wave monolithic integrated circuit (MMIC)
  - a definition
  - features of an MMIC
- reasons for operating in the millimetre-wave regime
  - frequencies, advantages
- mmW and MMIC technologies
- mmW system set-up
  - analogue front-end building blocks
- application examples
- prize considerations

analogue front-end



building blocks: frequency generation

Karlsruhe Institute of Technology

- radar
  - transmission signal
    - modulated: frequency-modulated continuous wave (FMCW), AM,...
    - pulsed
- communication
  - local oscillator (LO) for up- and down-conversion in mixers
  - fixed frequency or multiple carriers
- architectures
  - fundamental oscillator with phase-locked loop (PLL) stabilisation (phase noise reduction of free-running oscillator)
  - sub-harmonic oscillator with frequency multiplication

building blocks: frequency translation

- down-conversion
  - in communication systems: mixer to convert from RF to IF
  - in sensor systems (active and passive)
  - homodyne (mix with transmit signal, e.g. radar) or heterodyne (mix with LO) architectures
  - zero-IF or super-heterodyne receivers
  - direct detection: total power measurement by detector diode with (= zero-IF) or without down-conversion

- up-conversion
  - in communication and data transfer systems: mixer to convert from IF to RF
  - in radar: up-convert FMCW chirp signal generated at lower frequencies

building blocks: distribution network

- radiometers
  - Dicke switch
  - active, passive / hot, cold loads
  - polarisation selectivity

- radars
  - mono- or bi-static
  - phased-arrays
  - electronic beam steering

- communication
  - single input single output (SISO)
  - multiple input multiple output (MIMO)
  - antenna switch (Rx, Tx)

building blocks: signal amplification

- receiver
  - low noise amplifier (LNA)
  - noise figure, gain, …
- transmitter
  - power amplifier
  - efficiency, output power, linearity, …
- baseband
  - broadband amplifier
  - bandwidth dependent on
    - radar FMCW ramp
    - communication data-rate

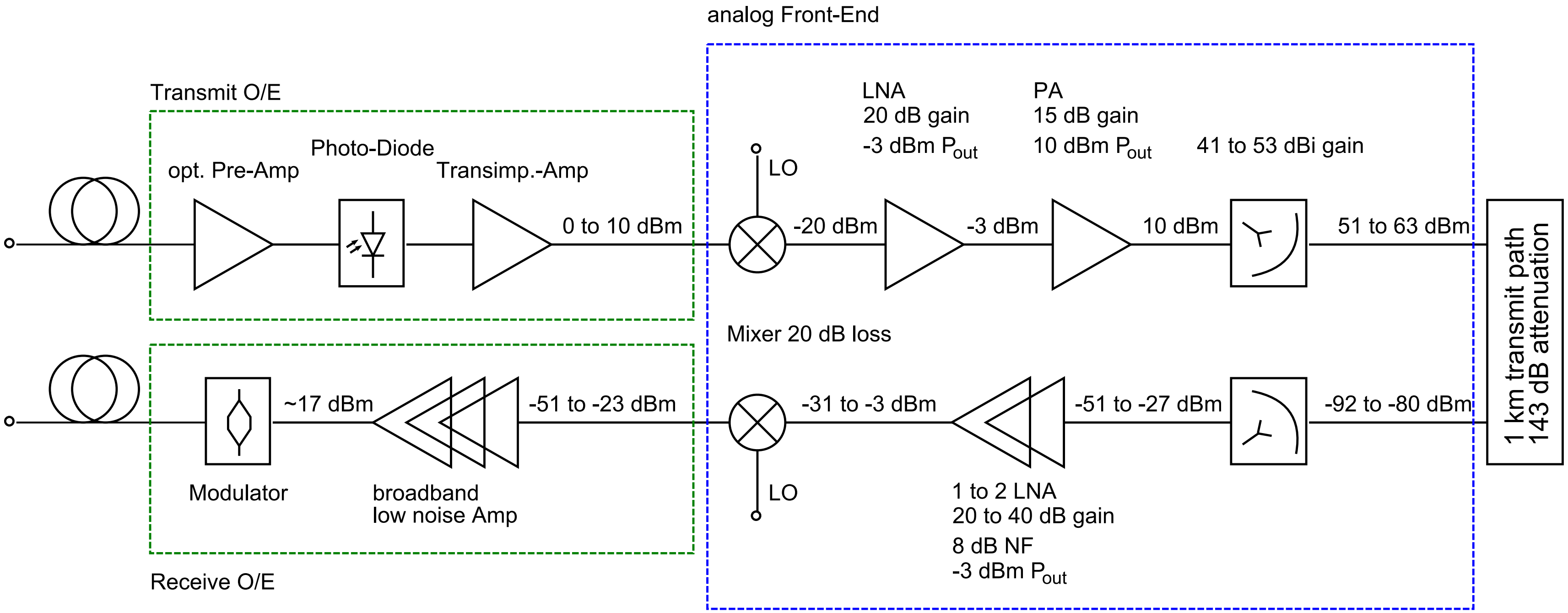
link budged calculations

- define IN/OUT power level, system range, margin, …

→ define antenna gain, LNA noise figure and gain, PA gain and power, …

→ are means to prevent malfunction necessary?

  - redundancy, peak power stability, …



overview

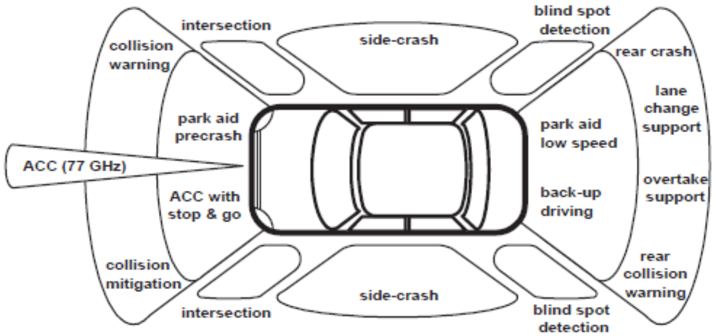
- Millimetre-wave monolithic integrated circuit (MMIC)
  - a definition
  - features of an MMIC
- reasons for operating in the millimetre-wave regime
  - frequencies, advantages
- mmW and MMIC technologies
- mmW system set-up
  - analogue front-end building blocks
- application examples
- prize considerations

Institut für Hochfrequenztechnik
und Elektronik

MMIC applications: commercial

- 60 GHz wireless comm.
  - wireless data rates up to 10Gbps
  - freq. allocation: 57-66GHz
  - application scenarios
    - home theatre (HDT)
    - Gbit WLAN
    - media kiosk
    - medical imaging (e.g. MRI)
    - fast data synchronisation
    - car-to-X communication

- 24 and 77 GHz automotive radar



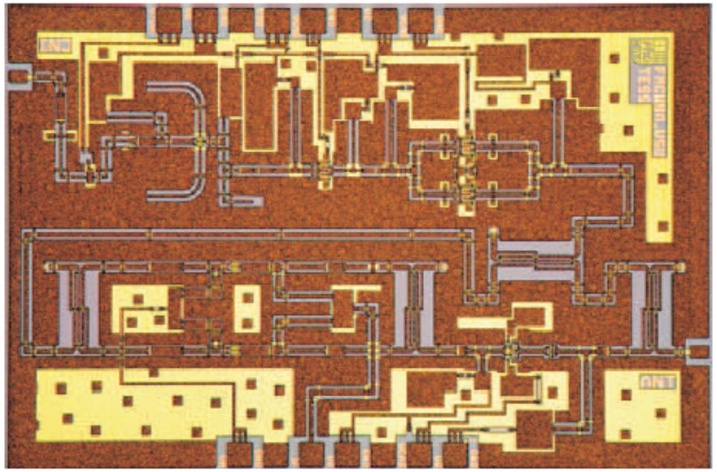
- sensing and radar for security
  - body scanner “Nacktscanner”

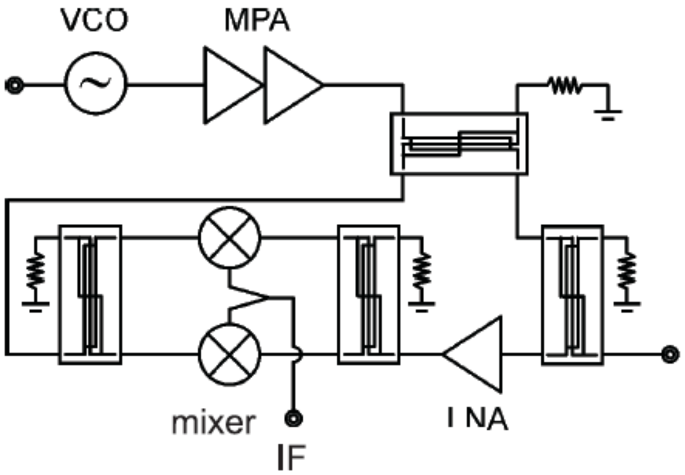
MMIC applications: 94 GHz FMCW radar

- transmitter
  - voltage-controlled oscillator
  - medium power amplifier
  - Lange-coupler

- receiver
  - Lange-coupler
  - low-noise amplifier
  - balanced mixer

- helicopter landing aid (brown-out)
- surveillance (e.g. in UAVs)
- material inspection
- ranging and localisation
- visual aid for fire fighting

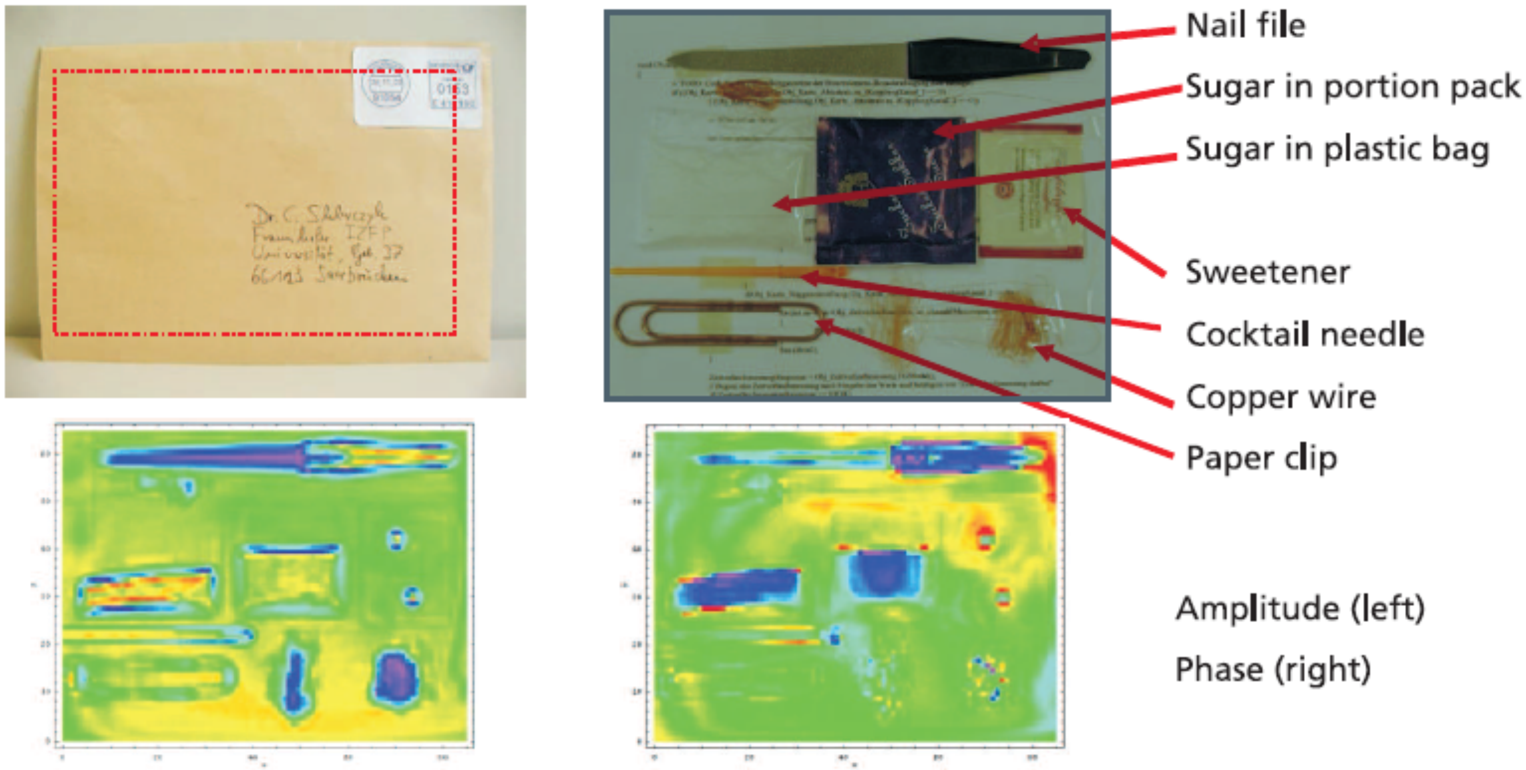




94 GHz FMCW, Fraunhofer IAF

MMIC applications: 94 GHz imaging

- mm-waves penetrate packaging and clothing
- detection and localisation of metallic and non-metallic items

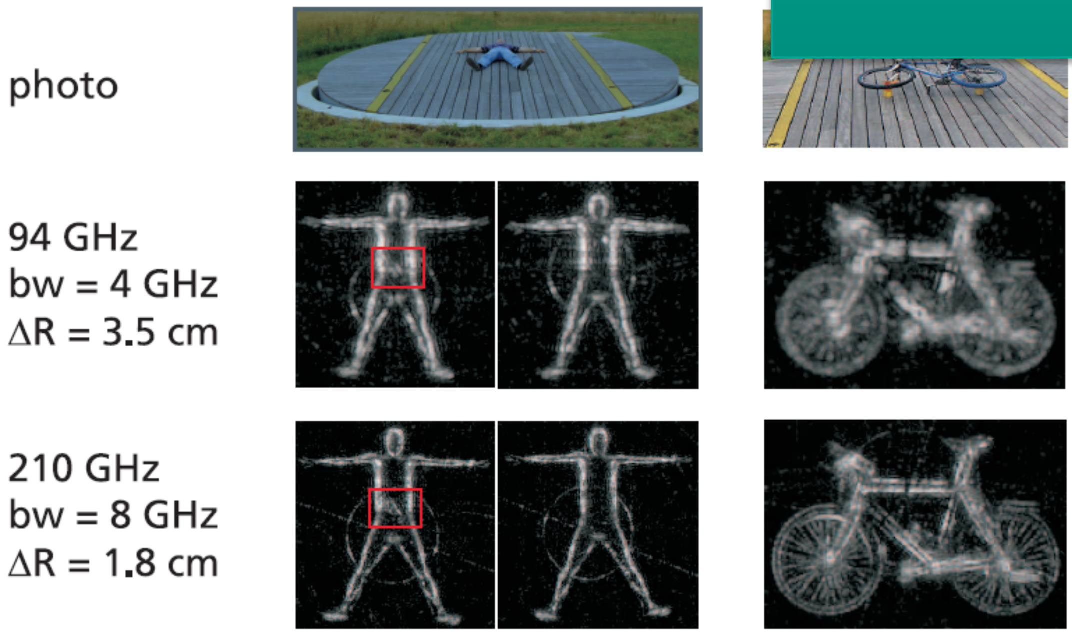


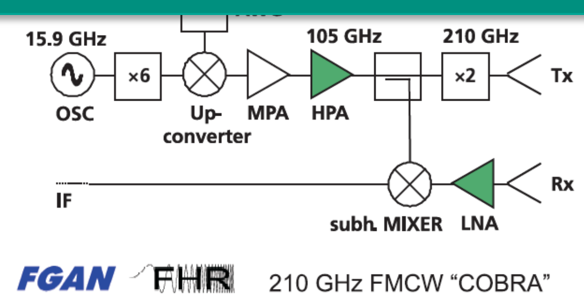
FMCW radar images at 94 GHz

Institut für Hochfrequenztechnik und Elektronik

MMIC applications: 210 GHz FMCW radar

- Fraunhofer FHR COBRA 210 GHz
  - linear chirp FMCW w/ chirp length
  - bandwidth: 8 GHz
- higher radar bandwidth results in hi
  geometrical resolution
- ISAR scenario: distance 150 m, hei
  turntable 10°tilted

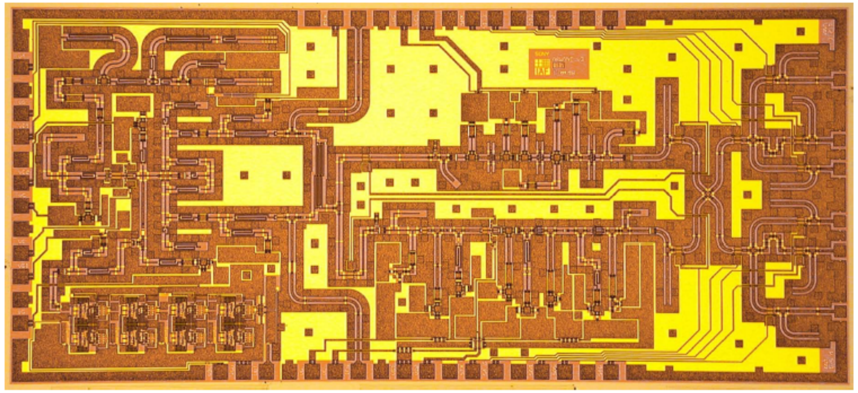




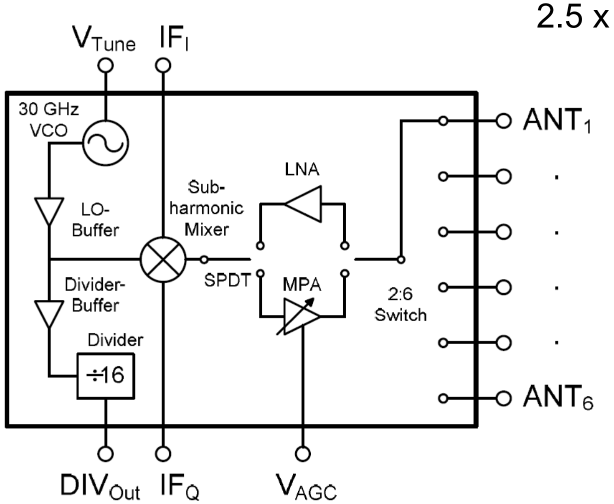
MMIC applications: 60 GHz wireless comm.

- single-chip Rx/Tx
- Fraunhofer IAF 100 nm gate-length mHEMT
- Operating frequency range
  - RF: 55 – 65 GHz
  - IF: DC – 3 GHz
- MMIC building blocks
  - SPDT and 2:6 switch
  - noise amplifier (LNA)
  - variable gain medium power amplifier (MPA)
  - sub-harmonic resistive IQ-mixer
  - voltage controlled oscillator (VCO)
  - LO / divider buffer amplifier
  - static divider (4 times by 2)

Koch et. al: A Fully Integrated, Compound Transceiver MIMIC utilizing Six Antenna Ports for 60 GHz Wireless Applications



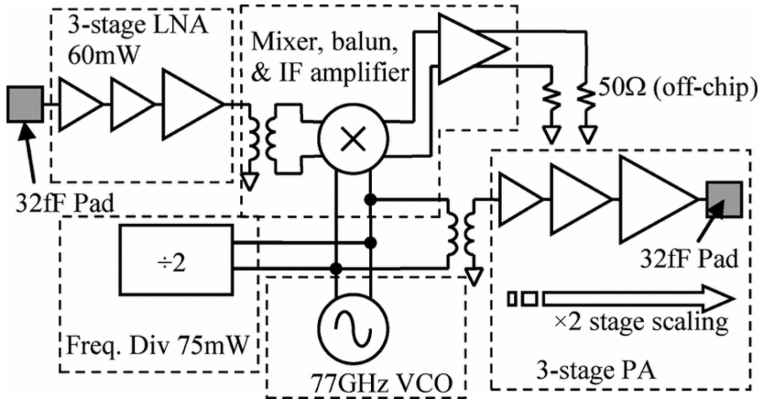
2.5 x 5.5 mm2

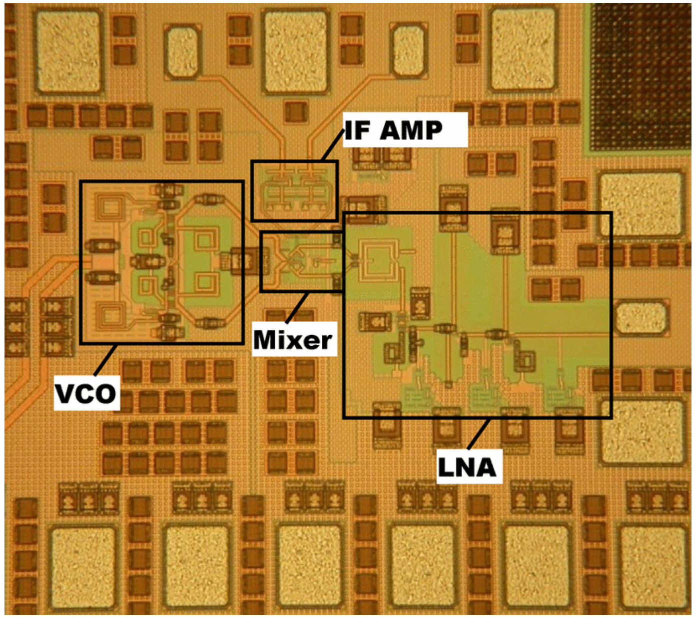


MMIC applications: 77 GHz automotive radar

- Doppler radar and imaging applications
- fabricated in SiGe HBT and SiGe BiCMOS technologies
- 65 nm CMOS
- conventional MMIC technique using thin-film microstrip (TFM) transmission line matching

- MMIC building blocks
  - double-balanced mixer
  - IF amplifier
  - VCO
  - power amplifier
  - LNA



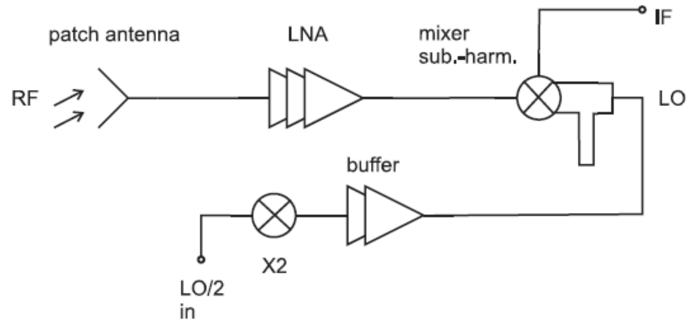


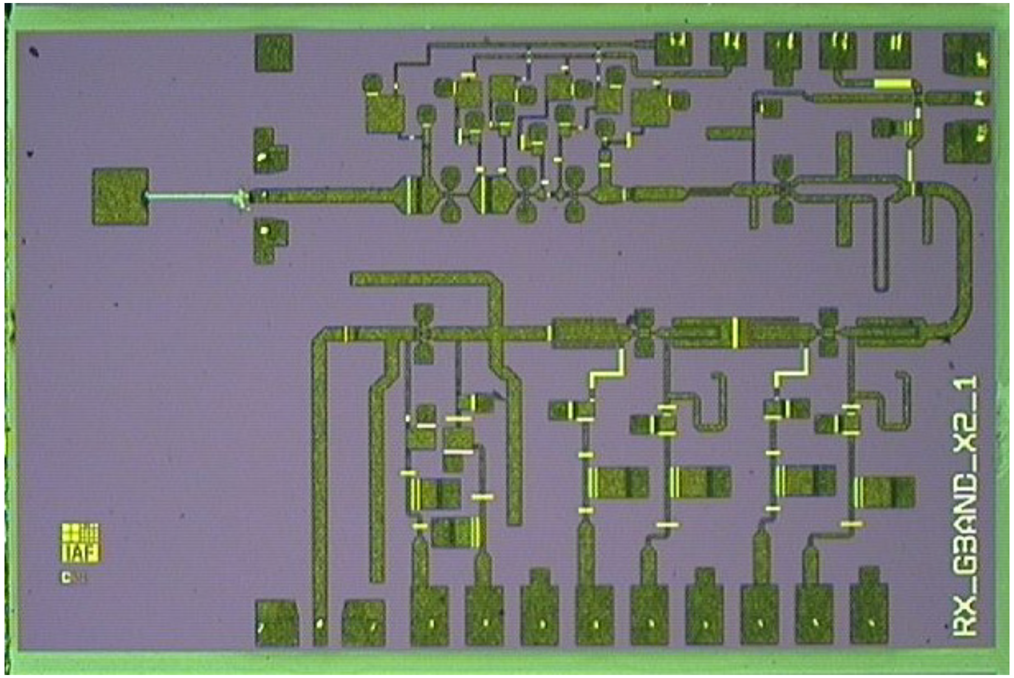
515 x 460 µm2

Nicolson et. al.: A Low-Voltage SiGe BiCMOS 77-GHz Automotive Radar Chipset

MMIC applications: 210 GHz imaging

- IAF Fraunhofer 100 nm InAlAs/InGaAs mHEMT
- 50 µm thick GaAs substrate
- microstrip transmission lines with transistor source via-holes
- operating frequency range
  - RF: 195 – 225 GHz
  - IF: 2 GHz
- MMIC building blocks
  - LO frequency doubler
    - 2-stage buffer amplifier
  - subharmonic resistive mixer
  - 3-stage low-noise amplifier
  - on-chip patch antenna





Zirath et. al.: Integrated receivers up to 220 GHz utilizing GaAs-mHEMT technology

overview

- Millimetre-wave monolithic integrated circuit (MMIC)
  - a definition
  - features of an MMIC
- reasons for operating in the millimetre-wave regime
  - frequencies, advantages
- mmW and MMIC technologies
- mmW system set-up
  - analogue front-end building blocks
- application examples
- prize considerations

market considerations

- millimetre-wave market structure
  - highly fragmented
  - many niche applications: earth, life, material science...
  - many professional/industrial applications: production...
  - many military applications, some dual-use: aeronautics, safety & security...
  - few consumer, mass market applications

- the potential “killer” application: candidates for mass markets
  - automotive radar
  - 60 GHz wireless (“home theatre” etc.)

prize considerations per unit area

- technology cost per unit area

→ what can be done in silicon, will be done in silicon!

substrate	device	cost ($/mm^2)
Si	CMOS	~ 0.01
SiGe	HBT	0.1 – 0.5
GaAs	HEMT	1 – 2
InP	HEMT	10

- further considerations
  - cost for assembly and testing is comparable for all technologies
  - Si allows for on-chip integration of digital baseband functionalities
  - at mm-waves, cost for mounting, packaging and assembly becomes dominant

    → mm-wave applications for mass markets require low-cost packaging

Institut für Hochfrequenztechnik und Elektronik

prize considerations: mask-set cost

- mask-set cost

→ Si-based technologies require mass market (communication, automotive) to be prize-competitive

device	cost (€ / mask-set)
Si-CMOS	> 1 mio
SiGe-HBT	> 100,000
3-5 HEMT	10,000

- further considerations
  - design cycle: roughly 2 months production time + design and testing for all technologies
  - Si-based technologies are processed in batches (~20 wafers, 8”-12”) per run
  - GaAs-based technologies are processed by lots (4-6 wafers, 3”-6”) per run, e-beam writing of individual wafers

prize considerations: cost vs. #MMIC

- research an development
  - ~100 pieces
- prototyping
  - ~1000 pieces
- products
  - consumer
    > 1 mio. per year
  - professional
    > 100,000 per year