Why Computational Electromagnetics?

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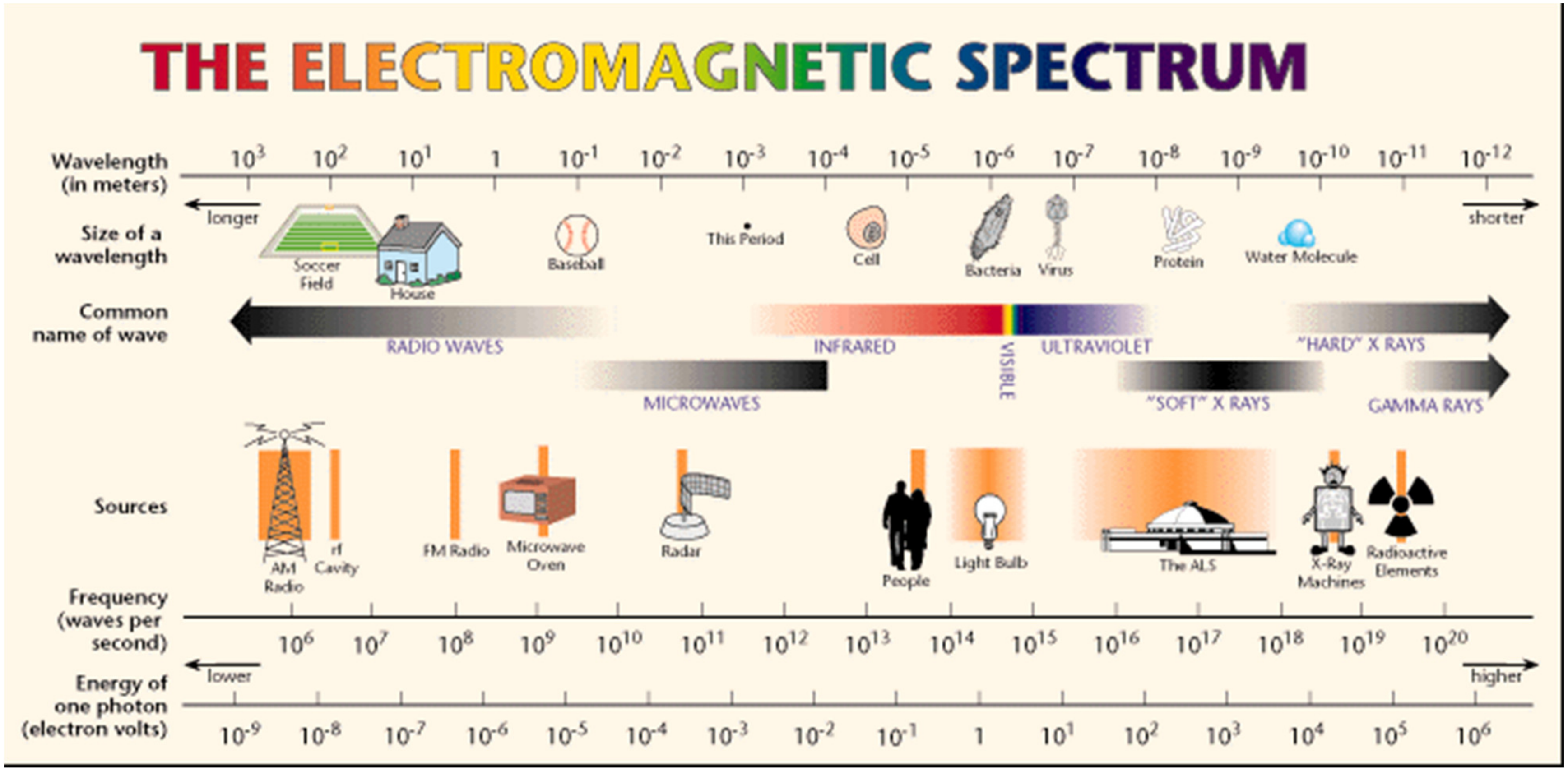
Content

INTRODUCTION

RF DEVICES AND THE NEED FOR COMPUTATIONAL ELECTROMAGNETICS

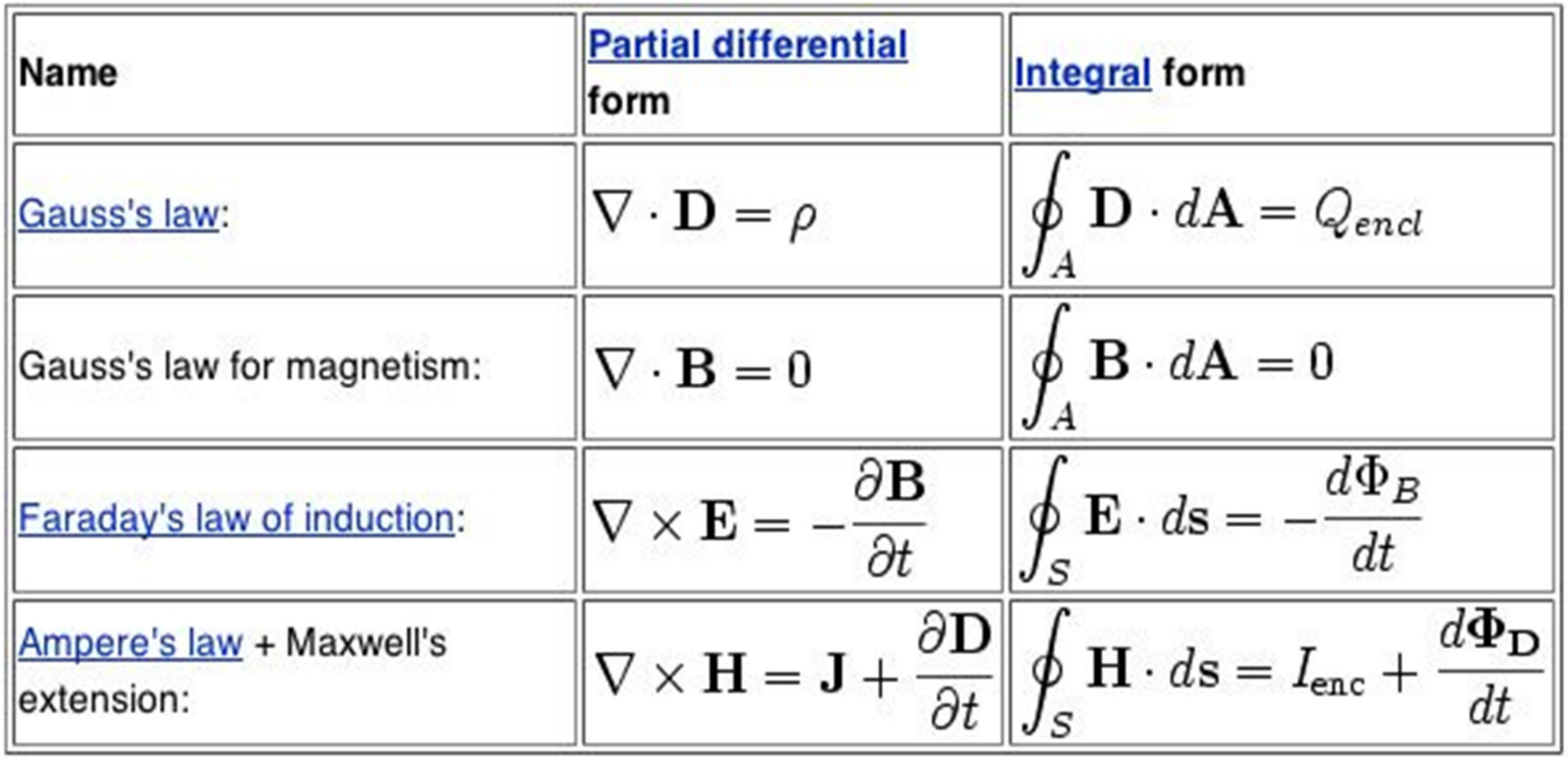
COMPUTATIONAL ELECTROMAGNETICS EXPLAINED

Introduction



Units:

- Charge: Q (*Coulomb=A.s*)
- Charge density ρ (C/m^3)
- Electric Field: $\boldsymbol{E}$ (V/m)
- Magnetic Field: $\boldsymbol{H}$ (A/m)
- Electric Displacement: $\boldsymbol{D}$ (C/m^2)
- Magnetic Induction: $\boldsymbol{B}$ (*Tesla* $=\mathrm{V.s/m}^2$)
- Current: I (A)
- Current density $\boldsymbol{J}$(A/m^2)



Name	Partial differential form	Integral form
Gauss's law:	$\nabla \cdot \mathbf{D} = \rho$	$\oint_A \mathbf{D} \cdot d\mathbf{A} = Q_{encl}$
Gauss's law for magnetism:	$\nabla \cdot \mathbf{B} = 0$	$\oint_A \mathbf{B} \cdot d\mathbf{A} = 0$
Faraday's law of induction:	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_S \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$
Ampere's law + Maxwell's extension:	$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint_S \mathbf{H} \cdot d\mathbf{s} = I_{\mathrm{enc}} + \frac{d\Phi_{\mathbf{D}}}{dt}$

Material Equations

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} = \varepsilon_r \varepsilon_0 \boldsymbol{E}$$

$$\boldsymbol{B} = \mu \boldsymbol{H} = \mu_r \mu_0 \boldsymbol{H}$$

$$\varepsilon_0 = 8.82 \times 10^{-12} (F/m) \qquad \mu_0 = 4\pi \times 10^{-7} (H/m)$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$$

Vacuum Impedance

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3 \times 10^8 m/s$$

Speed of light inVacuum

Applications of Electromagnetism: Wireless

Personal services

- cordless telephony
- cellular telephony → PCS
- mobile data transfer
- wireless LANs (local area network, bluetooth devices
- personal satellite communications
- global navigation/positioning systems (GPS)

Special services

- radars
- microwave relay links
- satellite systems (TV, telephony, data, military)
- radio astronomy
- biomedical engineering (imaging)
- military communications, guidance, surveillance

Applications of Electromagnetism: “Wired”

“wired” and semiconductor technology

Cable communications (TV, data transport, telephony)

Digital and Analog Microelectronics

Power generation, power grids, power supply, power electronics

Electro-mechanical devices and machinery

photonics and optics

optical fibers

laser technology

photonic and infrared imaging and surveillance

RF Devices and the need for computational electromagnetics

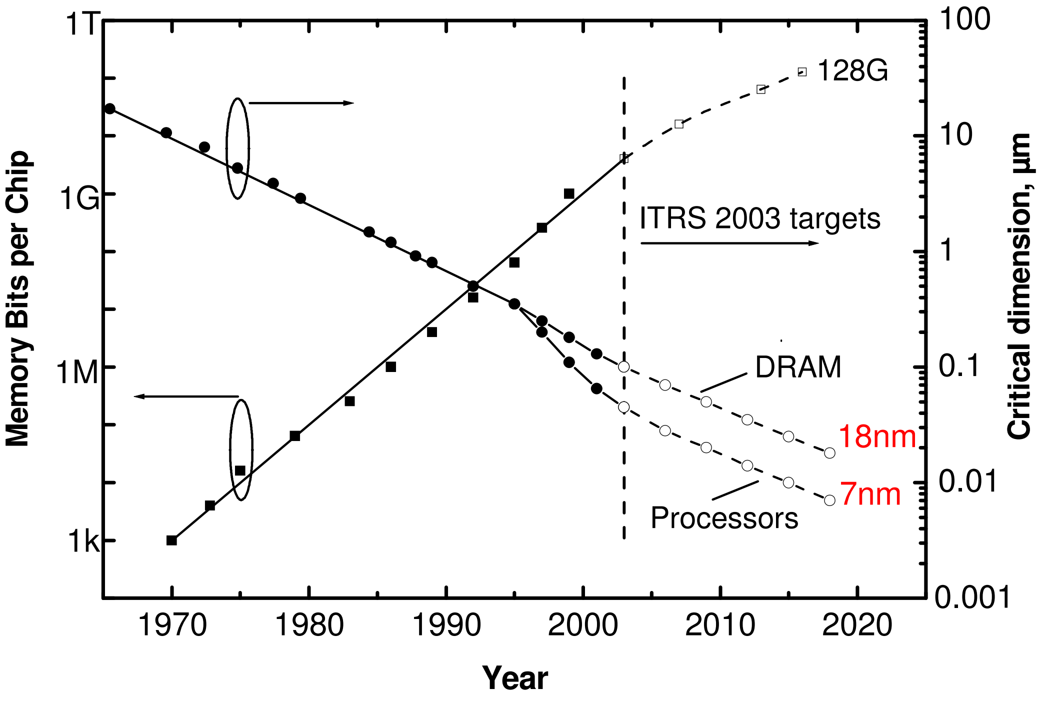
RF MOSFETs – Does This Work?

Traditional opinion: The Si MOSFET is a slow device not suitable for RF operation

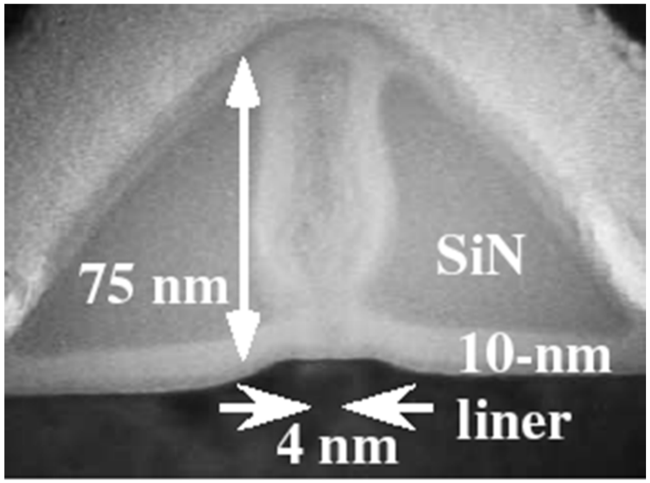
Truth:
- **The Si MOSFET is commonly slower than a III-V FET with comparable gate length**
- **VLSI electronics: Continuous scaling, i.e., shrinking of MOSFET size (gate length)**
- **Continuous scaling made Si MOSFETs not only smaller, but also much faster**

Today: The submicron MOSFET is capable of GHz operation!

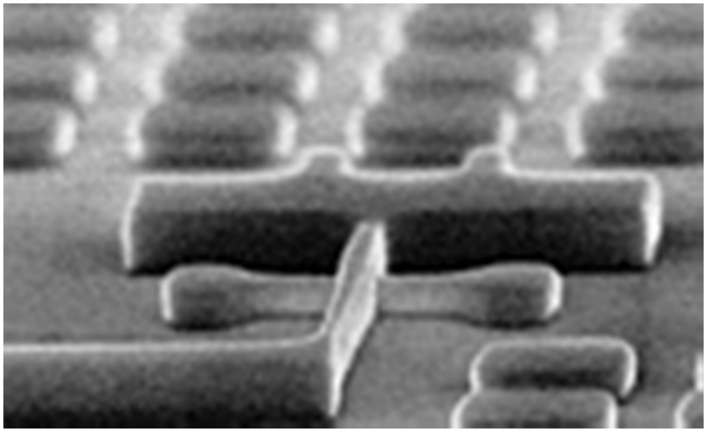
MOSFET Scaling



Evolution of Si VLSI: Moore's Law Minimum feature size and memory bits per chip vs year



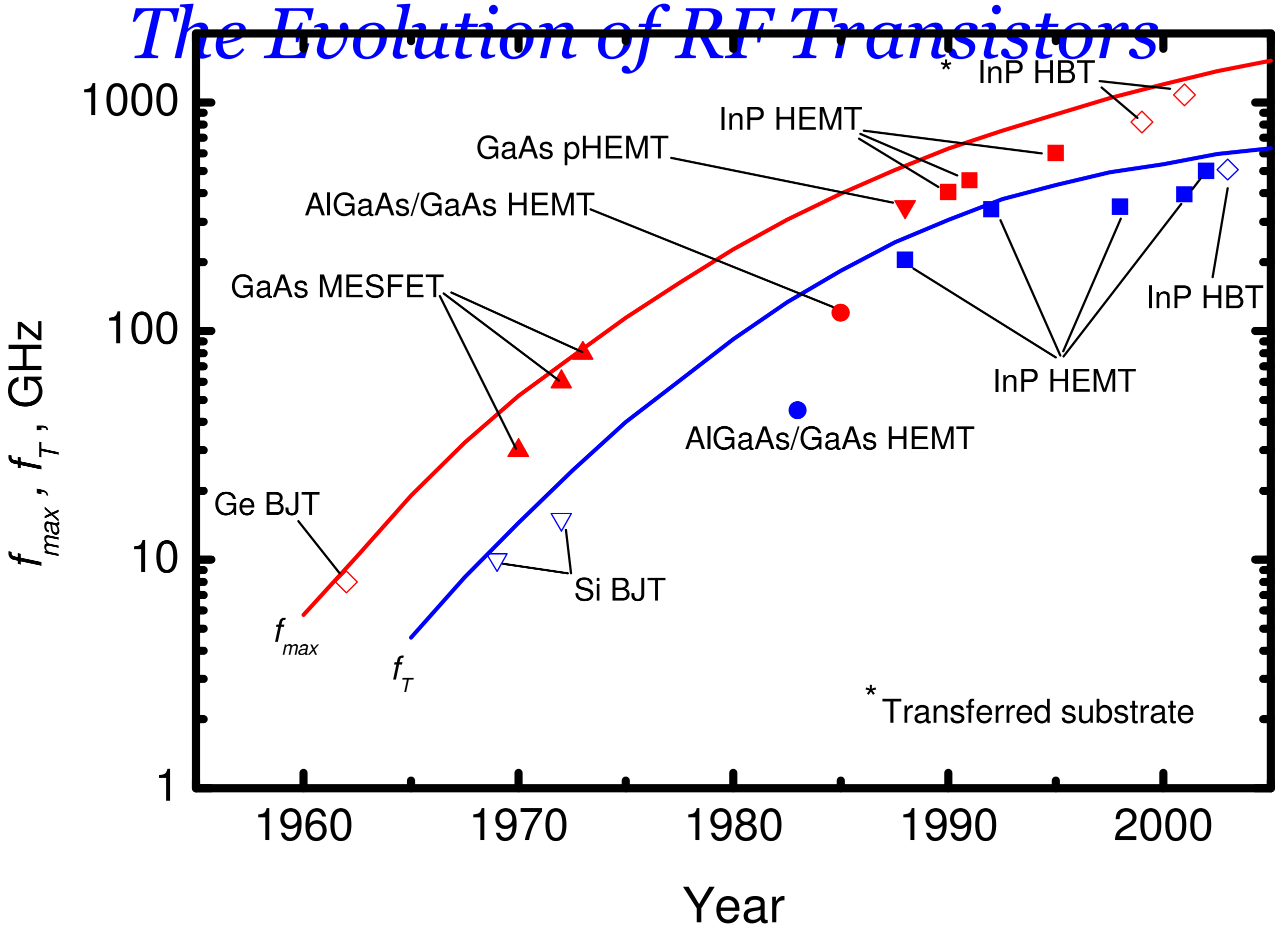
NEC IEDM Dec. 2003
5nm MOSFET



Intels new Trigate MOSFETs

New MOSFET concepts for future generations

The Evolution of RF Transistors



Important Trends:

- **Continuous increase of the frequency limits, i.e. f_T and f_{max} (III-V's)**
- **Increase of output power (wide bandgap transistors)**
- **Low-cost RF transistors for consumer mass markets (Si-based)**

Overview - Material Properties

Important for high f_T and f_{max} and low noise:

Fast carriers (i.e. μ_0, v_{peak} , v_{sat})

Important for high output power:

- high breakdown field and voltage, i.e. wide bandgap
- high thermal conductivity

	Si	GaAs	InGaAs*	4H SiC	6H SiC	GaN
E_G, eV	1.1	1.4	0.7	3.2	3	3.4
E_{BR}, 10^5 V/cm	5.7	6.4	4	33	30	40
μ_0, cm²/Vs	710	4700	7000	610	340	680
v_{peak}, 10^7cm/s	1	2	2.5-3	2	2	2.5
v_{sat}, 10^7cm/s	1	0.8	0.7	2	2	1.5-2
κ, W/cm-K	1.3	0.5	0.05	2.9	2.9	1.2**

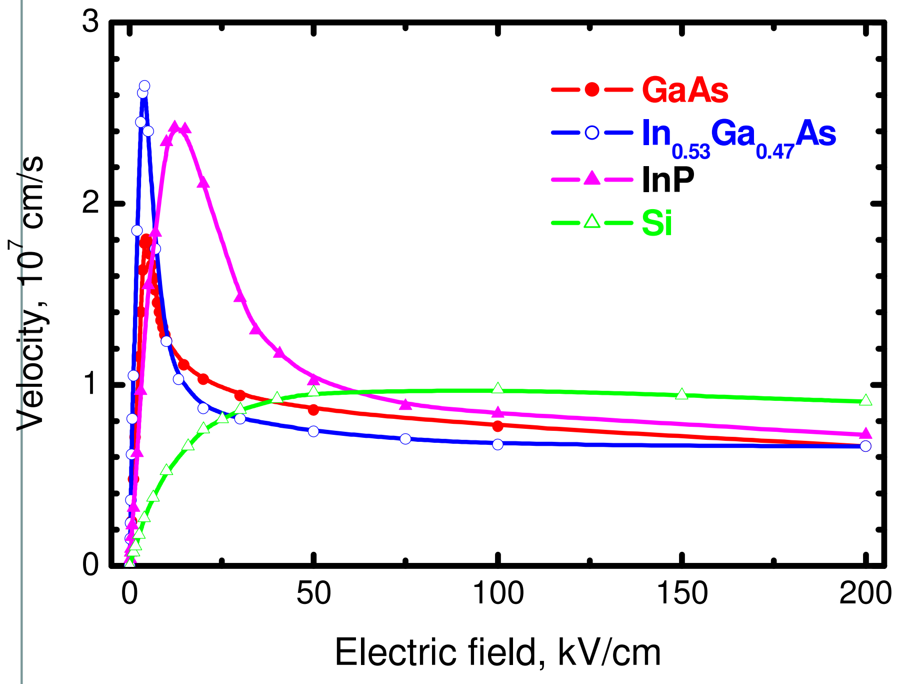
*$In_{0.47}Ga_{0.53}As$
** Saphir 0.43

Data for n-type bulk material, $N_D = 10^{17}$ cm^{-3}

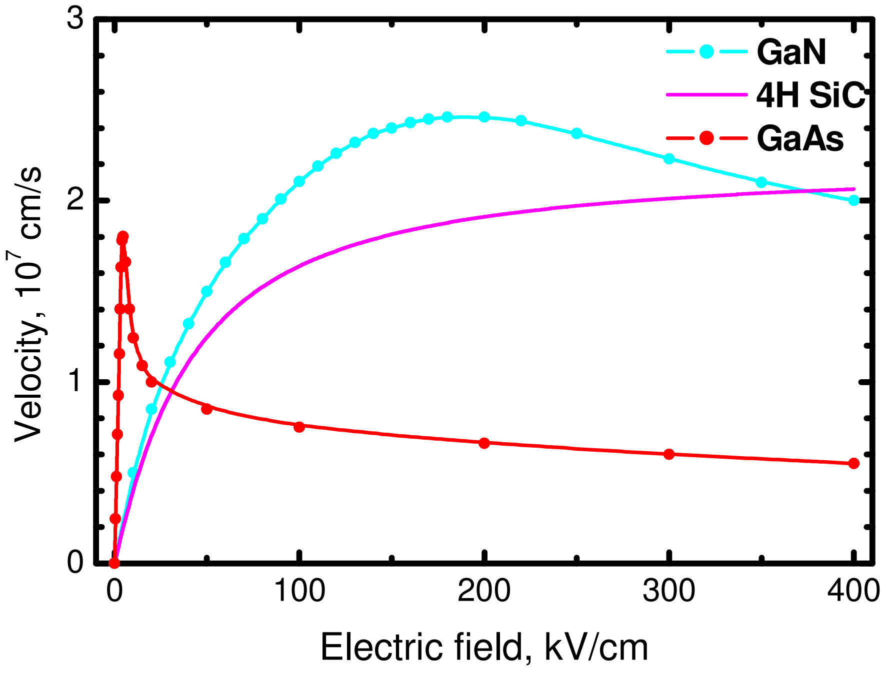
Carrier Transport (Electrons)

Stationary velocity-field characteristis (*v*-*E*)
Bulk material

Si and III-V's



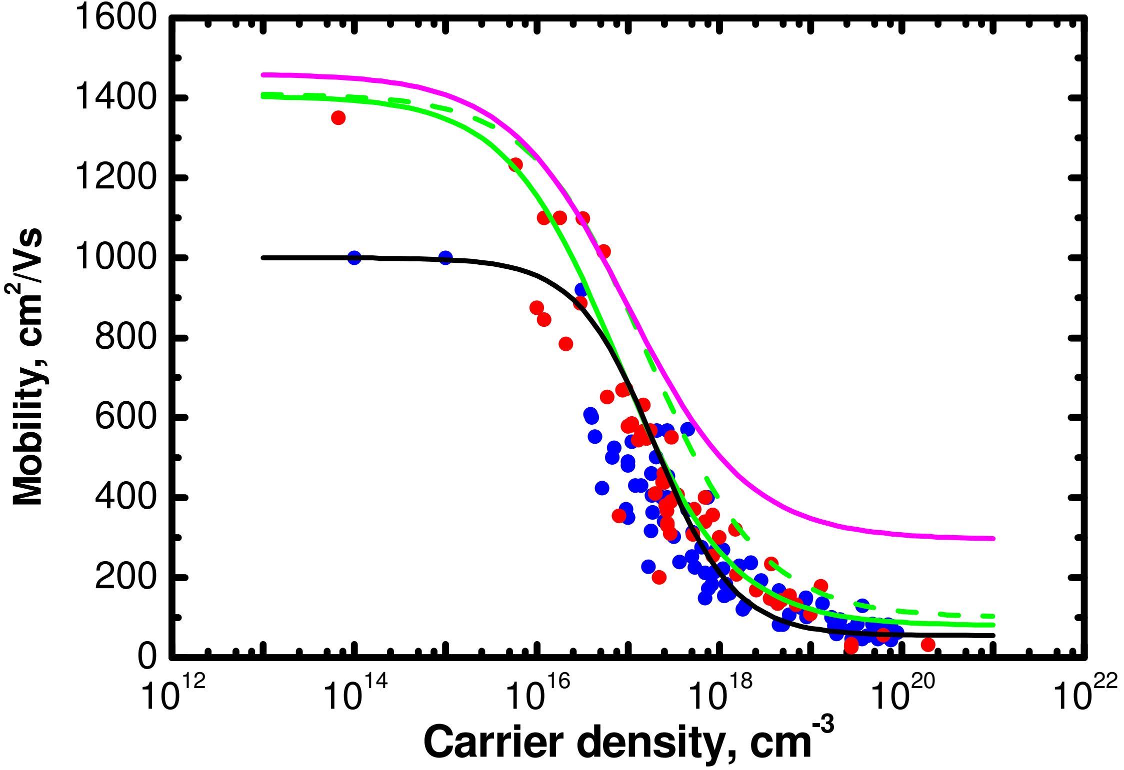
Wide bandgap semiconductors



- **Lower velocity at low fields**
- **Higher velocity at high fields**

Carrier Transport in Bulk GaN

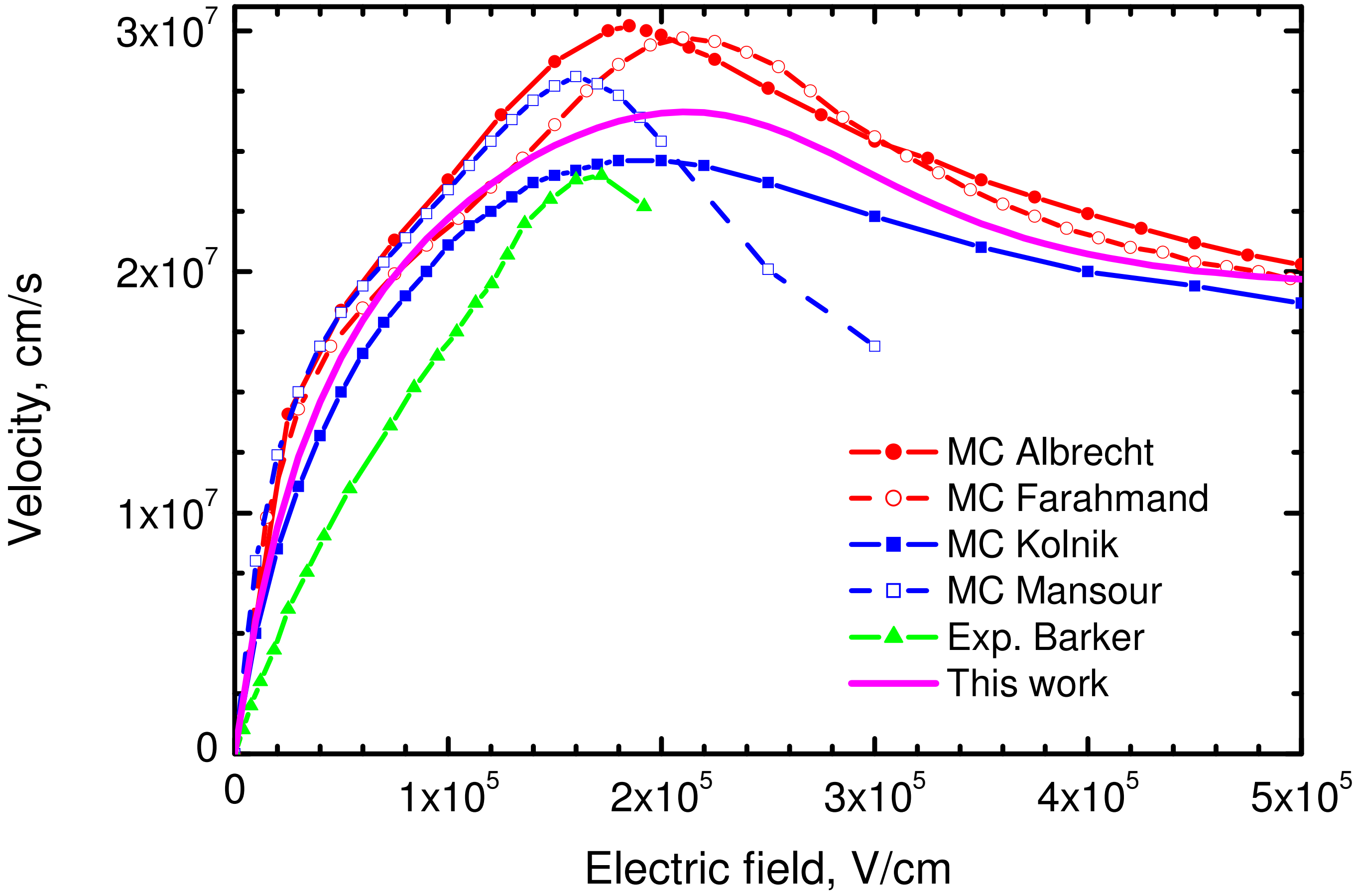
Low-field electron mobilty



$$\mu_0 = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{n}{n_{ref}}\right)^{\alpha}}$$

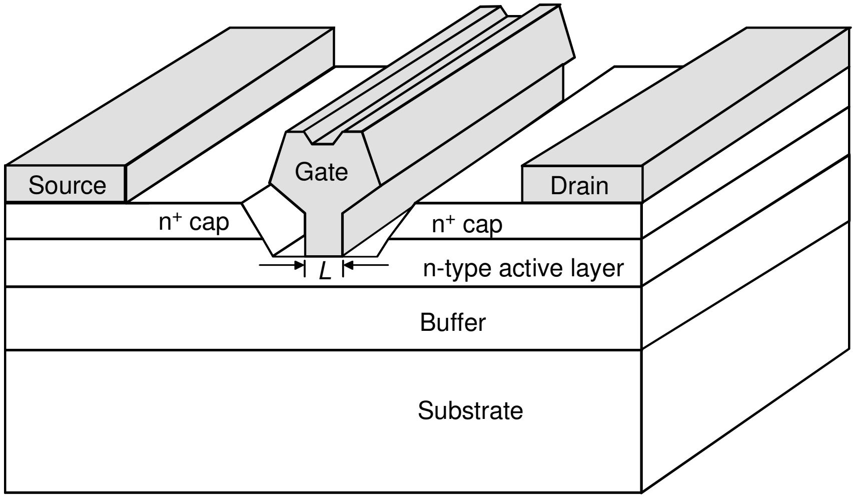
Fit	Average	Upper Limit
μ_{min}, cm^2/Vs	80	100
μ_{max}, cm^2/Vs	1405	1410
n_{ref}, 10^{17} cm^{-3}	0.778	1.66
α	0.71	0.691

Carrier Transport in Bulk GaN

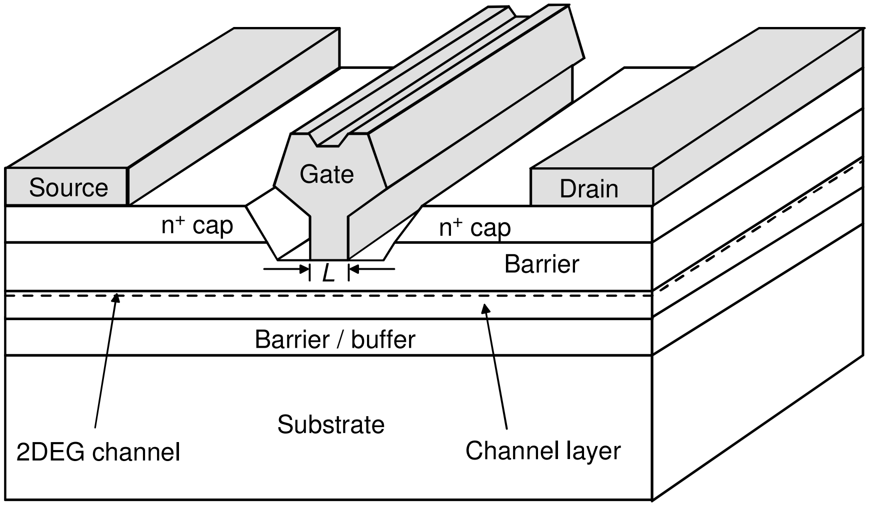


$$v(E) = \frac{\mu_0 E + v_{sat}(E/E_c)^{n_1}}{1 + (E/E_c)^{n_1} + n_2 (E/E_c)^{n_3}}$$

MESFETs and HEMTs



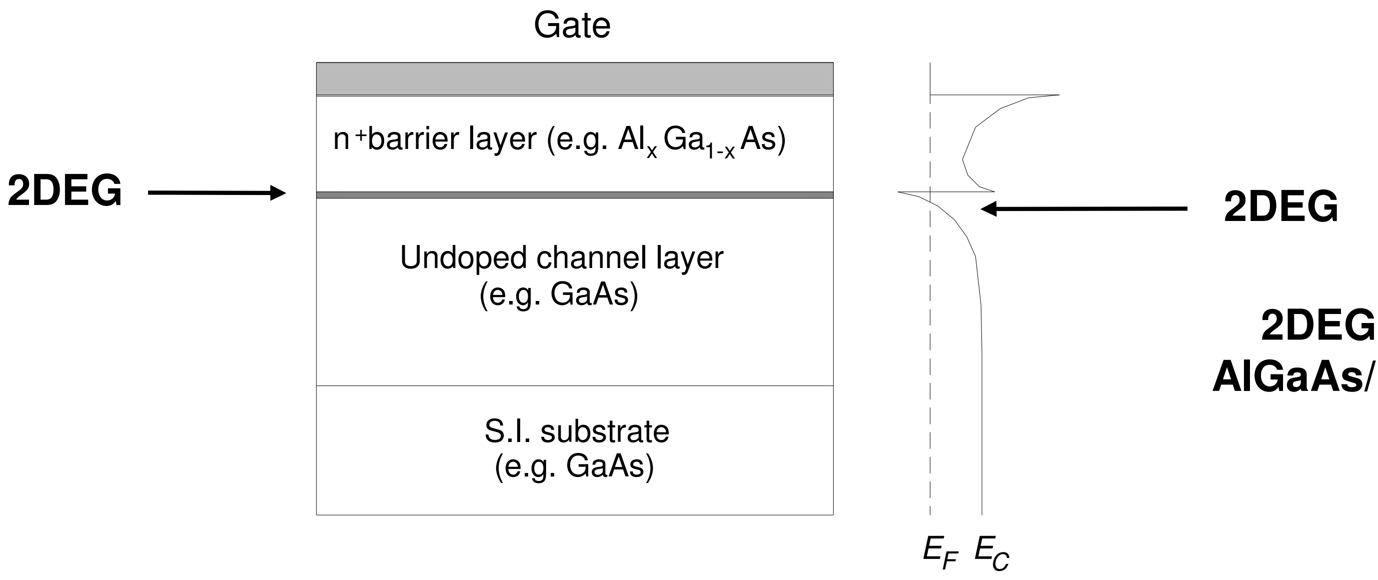
MESFET
Metal-Semiconductor FET
Channel: n-dotierte aktive Schicht



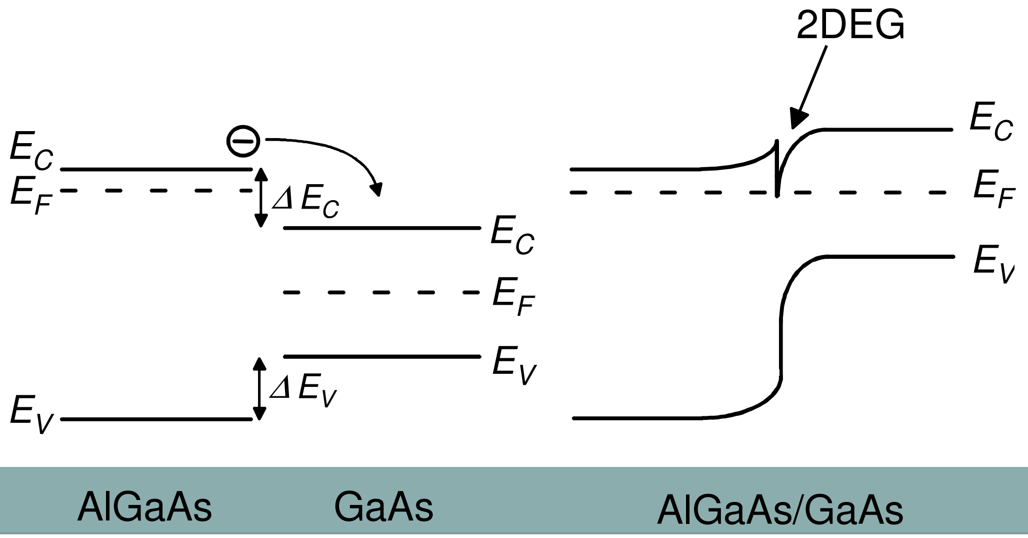
HEMT
High Electron Mobility Transistor
Channel: twodimensional electron gas (2DEG) at the interface channel layer - barrier

2DEGs

Two-Dimensional Electron Gas - 2DEG



2DEG in a conventional AlGaAs/GaAs HEMT-Struktur



2DEG electrons are spatially separated from the donator ions
→ high mobility!

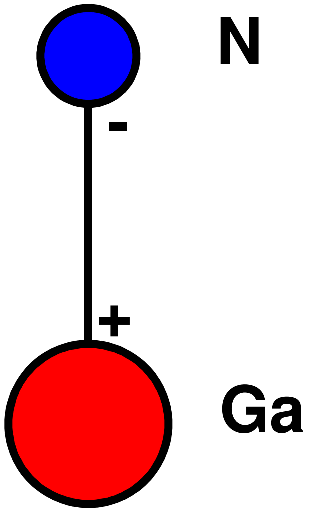
Properties of 2DEGs

Heterojunction Type	μ_0, cm^2/Vs	n_S, cm^{-2}	ΔE_G, eV	ΔE_C, eV
$Al_{0.3}Ga_{0.7}As/GaAs$	5400	1.4×10^{12}	0.38	0.22
$Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$	6400	2.2×10^{12}	0.58	0.41
$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$	10 000	3.0×10^{12}	0.71	0.52
$Al_{0.3}Ga_{0.7}N/GaN$	1 400	1.3×10^{13}	0.6	0.42

III-V heterostructures: - more In in the channel layer leads to higher mobility μ_0
- larger ΔE_C causes a higher higher sheet concentration n_S

AlGaN/GaN: - lower mobility than III-V's
- rather moderate ΔE_C but extremely high n_S - WHY ?

2DEGs in AlGaN/GaN Structures



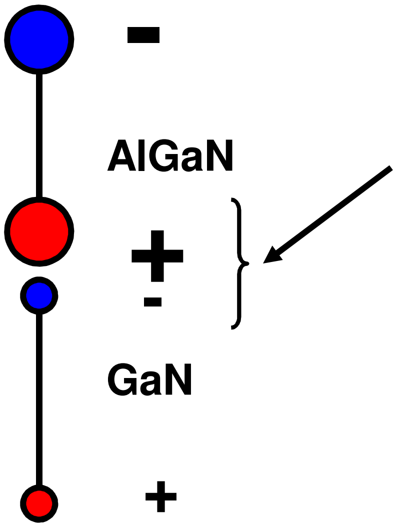
- Electronegativity
  polar nature of the bonds in AlGaN and GaN

- Deviation of the GaN and AlGaN crystal
  structure from the ideal structure:
  spontaneous polarization

- Different spontaneous polarizations in AlGaN and GaN
  gradient of the polarization at the interface

- Difference in the lattice constants in AlGaN and GaN
  strained AlGaN additional polarisation component:
  piezoelectric polarization

2DEGs in AlGaN/GaN Structures

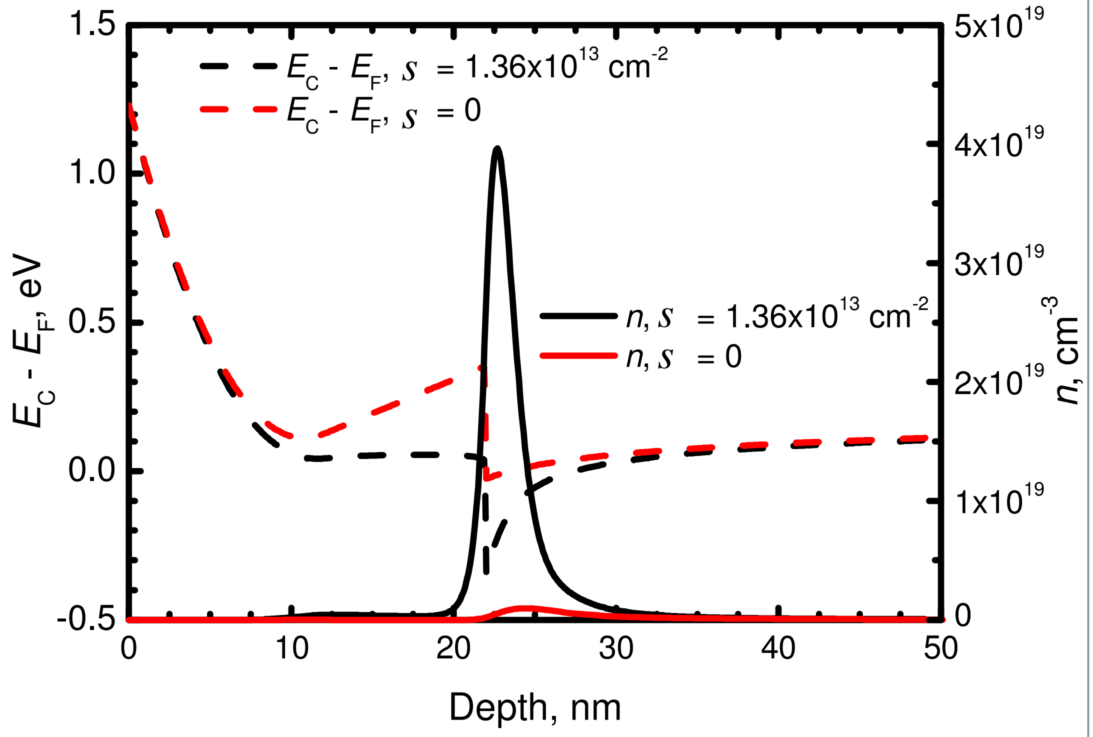


At the AlGaN/GaNinterface occurs a positive net charge

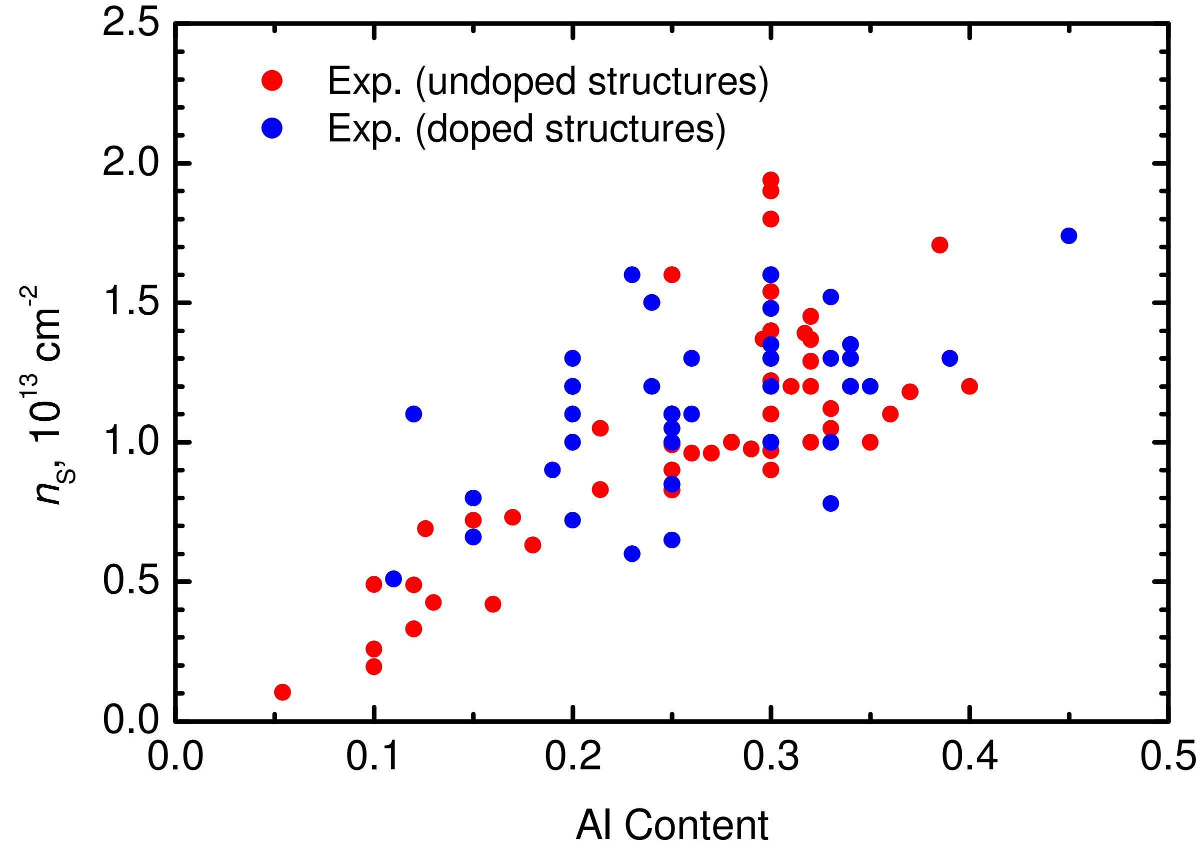
+ σ leading to the formation of a 2DEG in the GaN.

Two important messages:

- **Only a small portion of the 2DEG elecrons is caused by the barrier doping !**
- **Even without any doping very high 2DEG sheet concentrations are possible!**

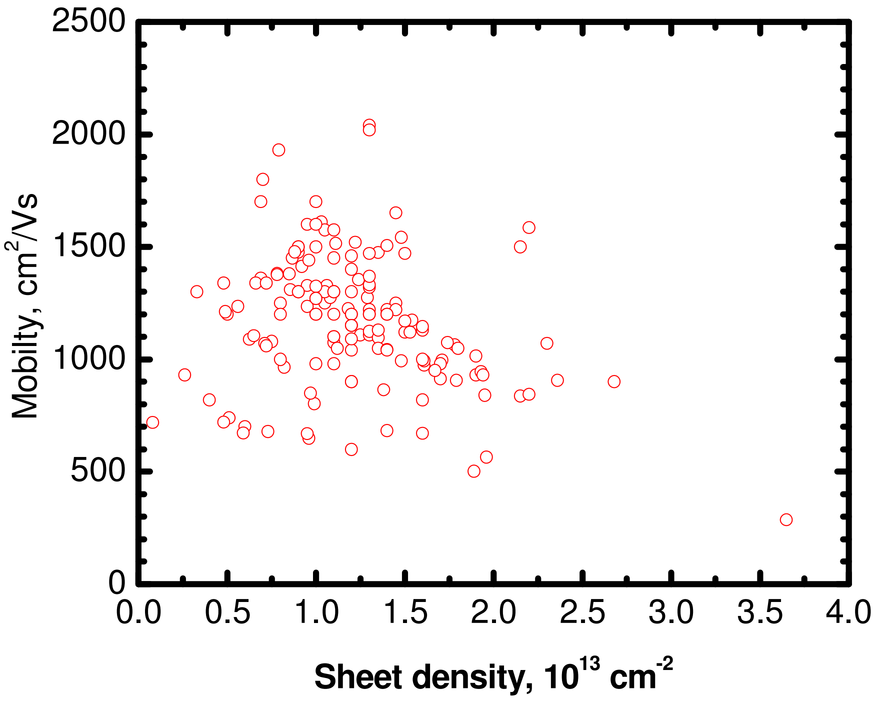


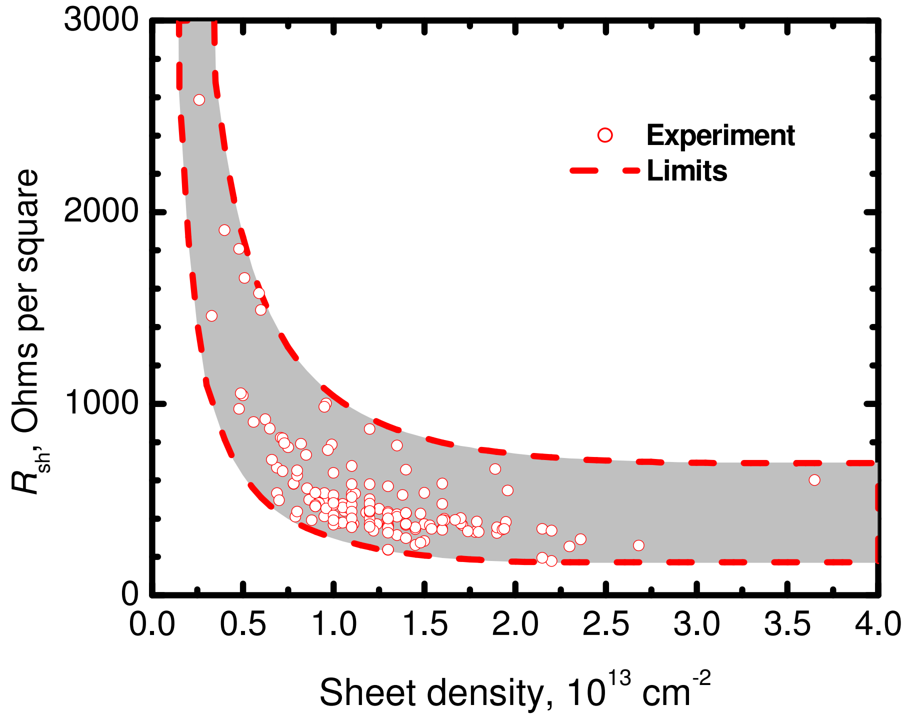
2DEGs in AlGaN/GaN Structures



Measured 2DEG sheet concentration n_S in $Al_xGa_{1-x}N$/GaN heterostructures vs. Al content x

Carrier Transport in AlGaN/GaN 2DEGs



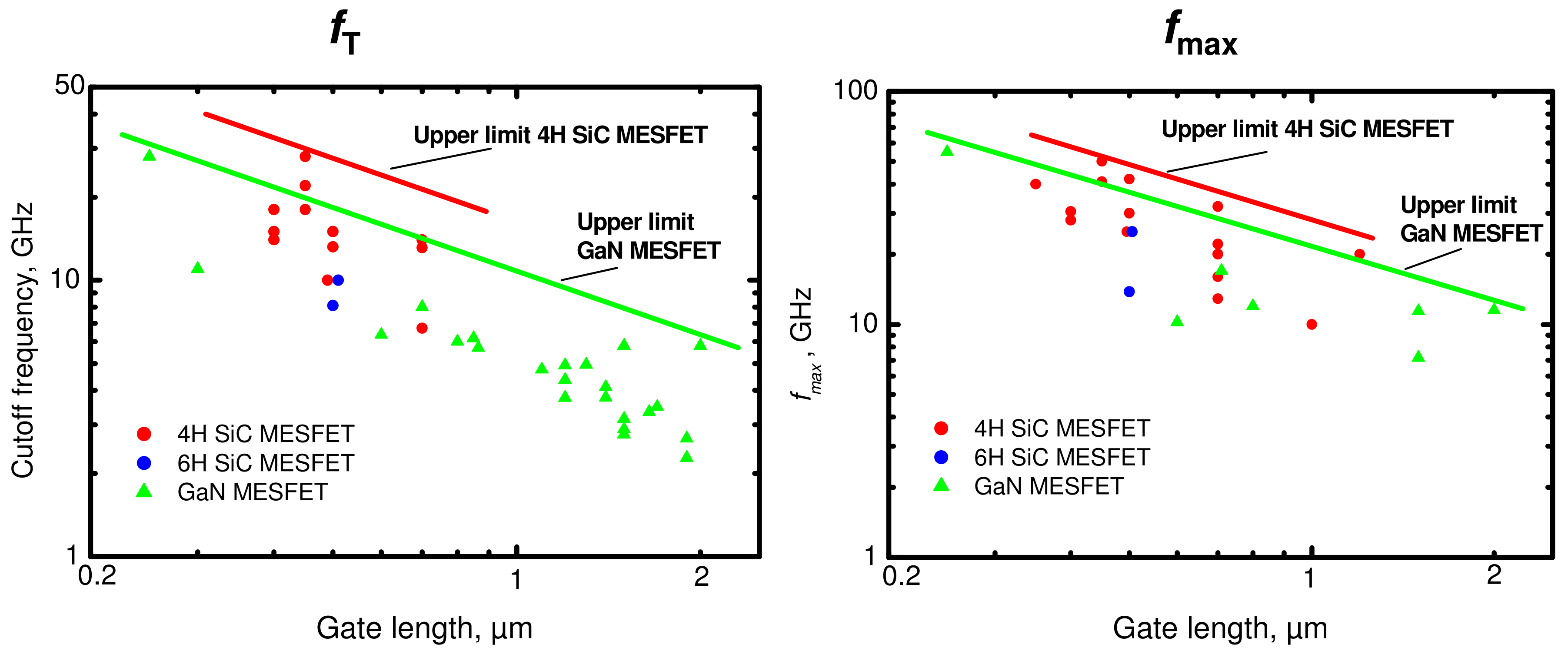


$$\longrightarrow$$

$$R_{sh} = \frac{1}{q\ \mu_0\ n_S}$$

SiC and GaN MESFETs

Frequency limits of SiC and GaN MESFETs vs. gate length



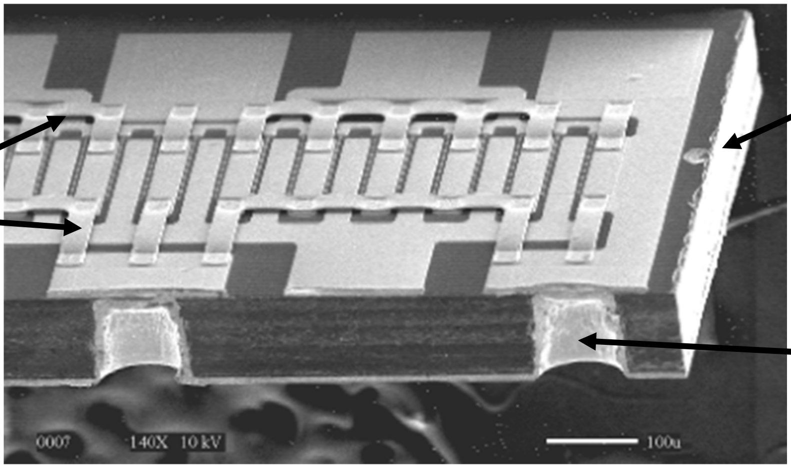
f_T

f_{max}

Record performance

Transistor type	f_T, GHz	f_{max}, GHz
SiC MESFET	28 (*L* = 0.45 µm, 2002)	50 (*L* = 0.45 µm, 1998)
GaN MESFET	28 (*L* = 0.25 µm, 2002)	55 (*L* = 0.25 µm, 2002)

SiC MESFETs



Air bridges

4H SiC Wafer
(thinned to 100 µm)

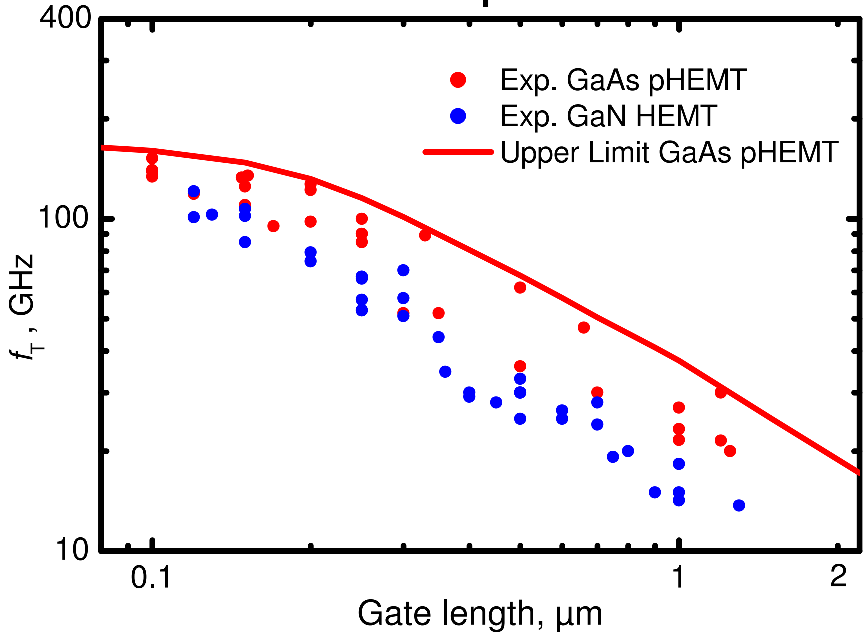
Source Vias

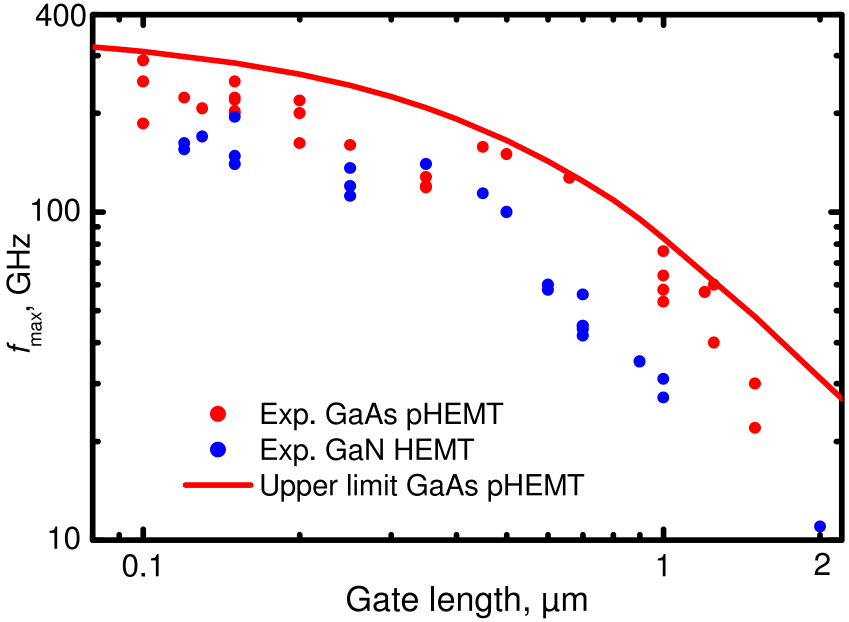
Experimental SiC MESFET (J. W. Palmour et al., Tech. Dig. IEDM, pp. 385-388, 2001, Cree)

Current Record Performance (Output Power)
P_{out} = 120 W bei 3 GHz (1999)
P_{Dout} = 7.2 W/mm bei 3.5 GHz (2002)

AlGaN HEMTs - Frequency Limits

Frequency limits of AlGaN HEMTs vs. gate length
(for comparison data of GaAs pHEMTs are also shown


f_T


f_{max}

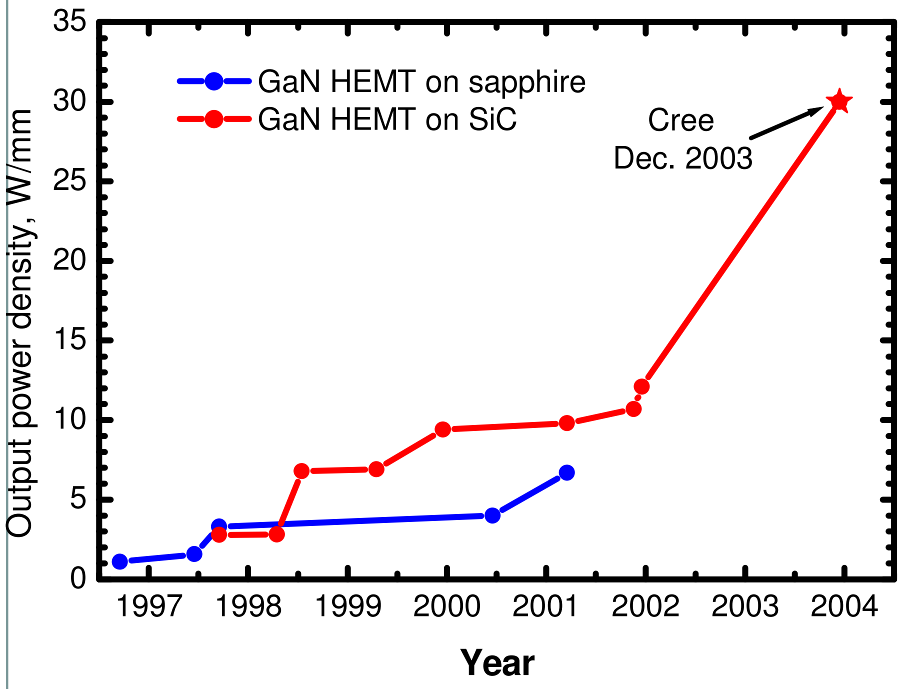
Record performance

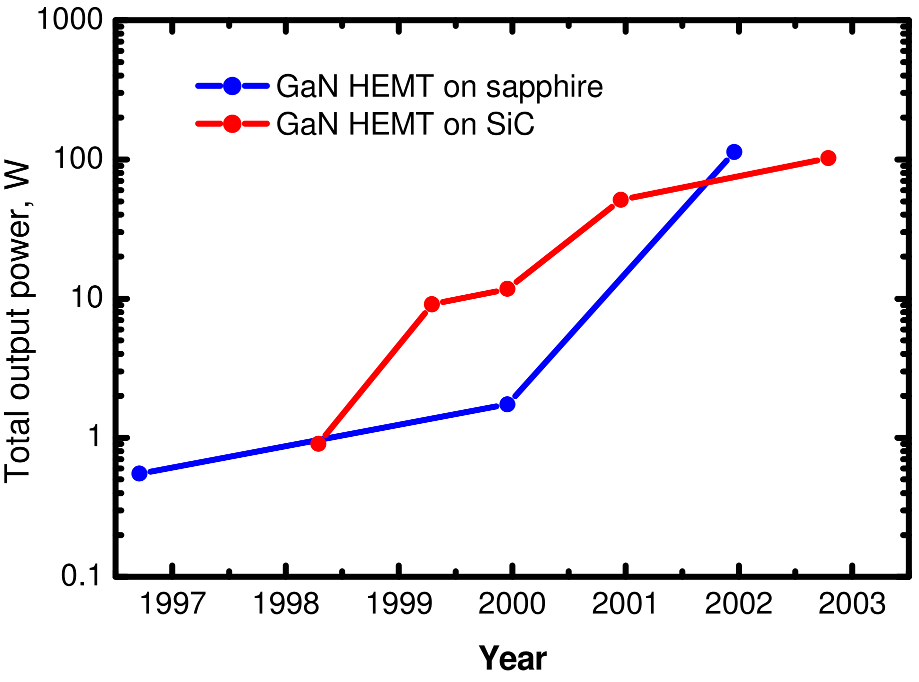
Transistortyp	**f_T, GHz**	**f_{max}, GHz**
AlGaN HEMT	**121 (*L* = 0.12 µm, 2002)**	**195 (*L* = 0.15 µm, 2002)**
GaAs pHEMT	**151 (*L* = 0.10 µm, 1989)**	**290 (*L* = 0.10 µm, 1990)**

AlGaN/GaN HEMTs - Evolution of Output Power

Output power density *P_{Dout}*

Output power *P_{out}*

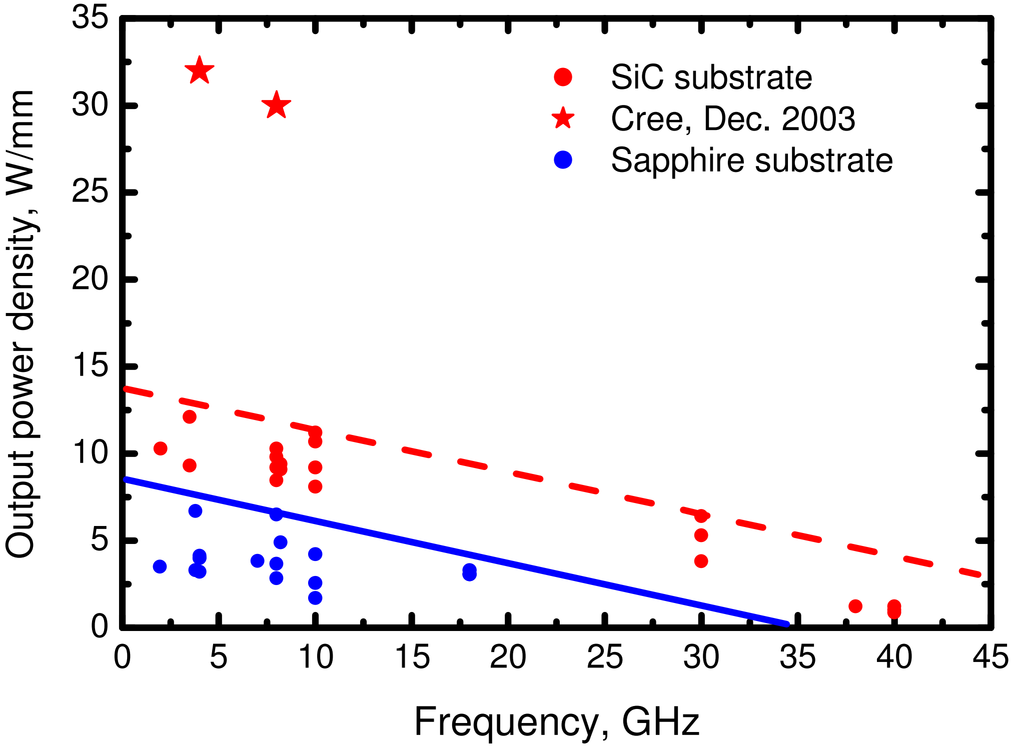




Continuous Improvement
of *P_{Dout}* und *P_D* in recent years

AlGaN/GaN HEMTs - Output Power Density P_{Dout}

Influence of the substrate material



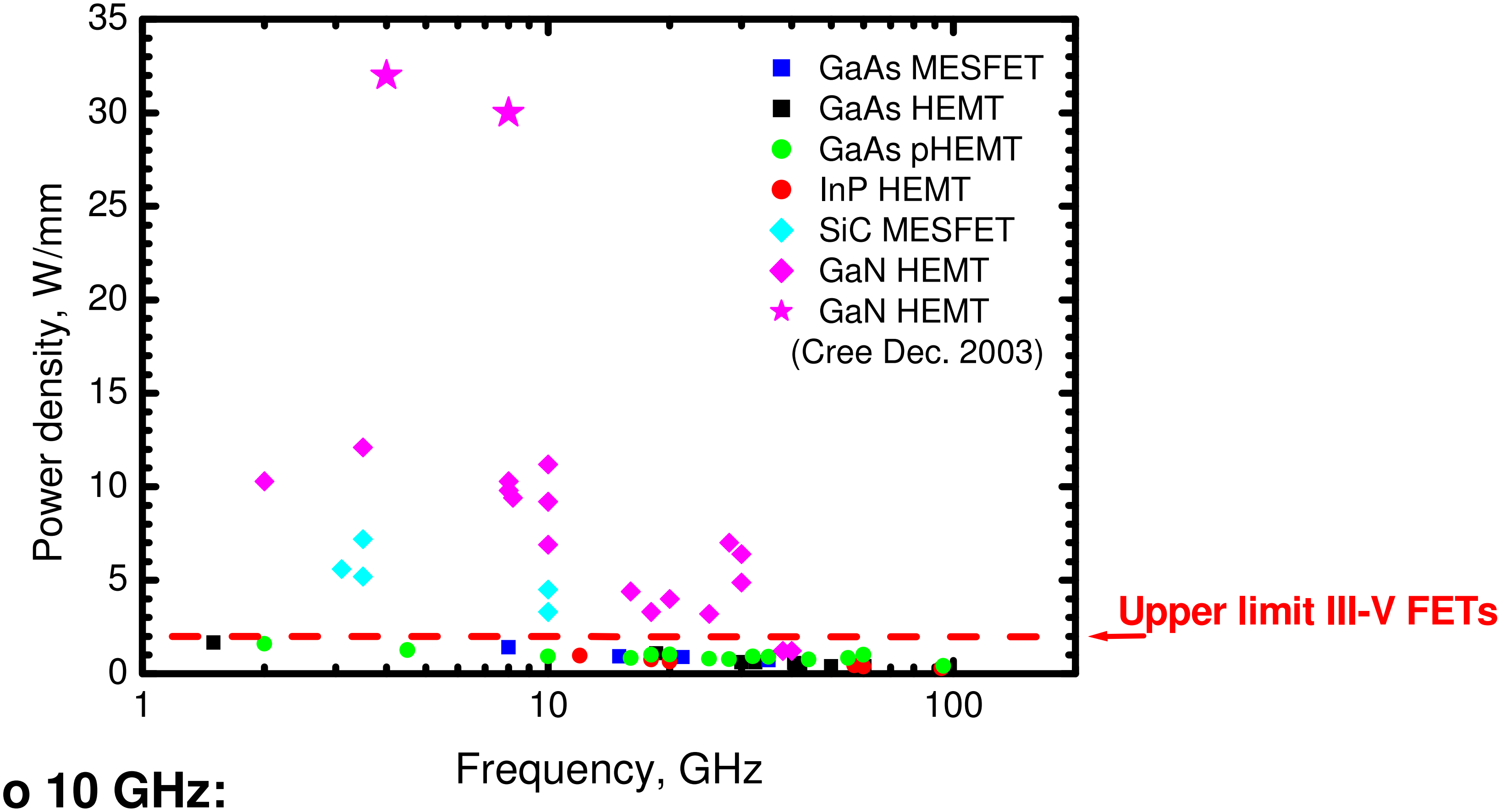
HEMTs on SiC substrates show considerably higher output power density.

Reason: Excellent thermal conductivity of SiC.

Note: Currently GaN substrates are not available.

Output Power vs. Frequency

Comparison of competing RF FETs



Up to 10 GHz:

- **The best AlGaN HEMTs show 30-fold (!) power density of III-V FETs**
- **The best SiC MESFETs show (5-8)-fold power density of III-V FETs**

Lessons Learned!

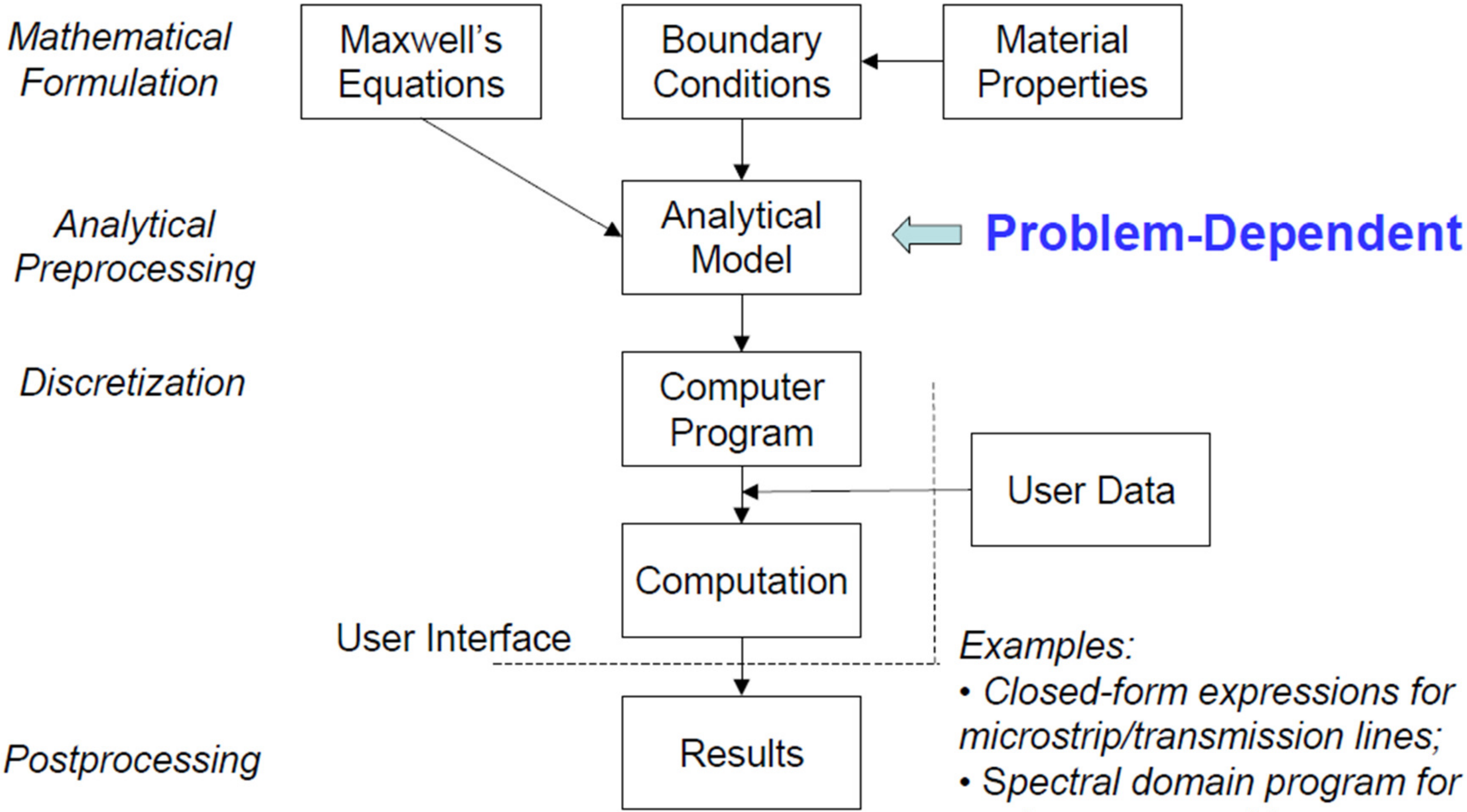
WE NEED TO SOLVE MAXWELL'S EQUATIONS TO BE ABLE TO PREDICT RF BEHAVIOR OF THE DEVICES PRESENTED IN THIS SECTION.

THE QUESTION IS:
HOW DO WE DO THAT?

THE ANSWER IS:
COMPUTATIONAL ELECTROMAGNETICS.

Computational Electromagnetics Explained

Classic Electromagnetic Solution

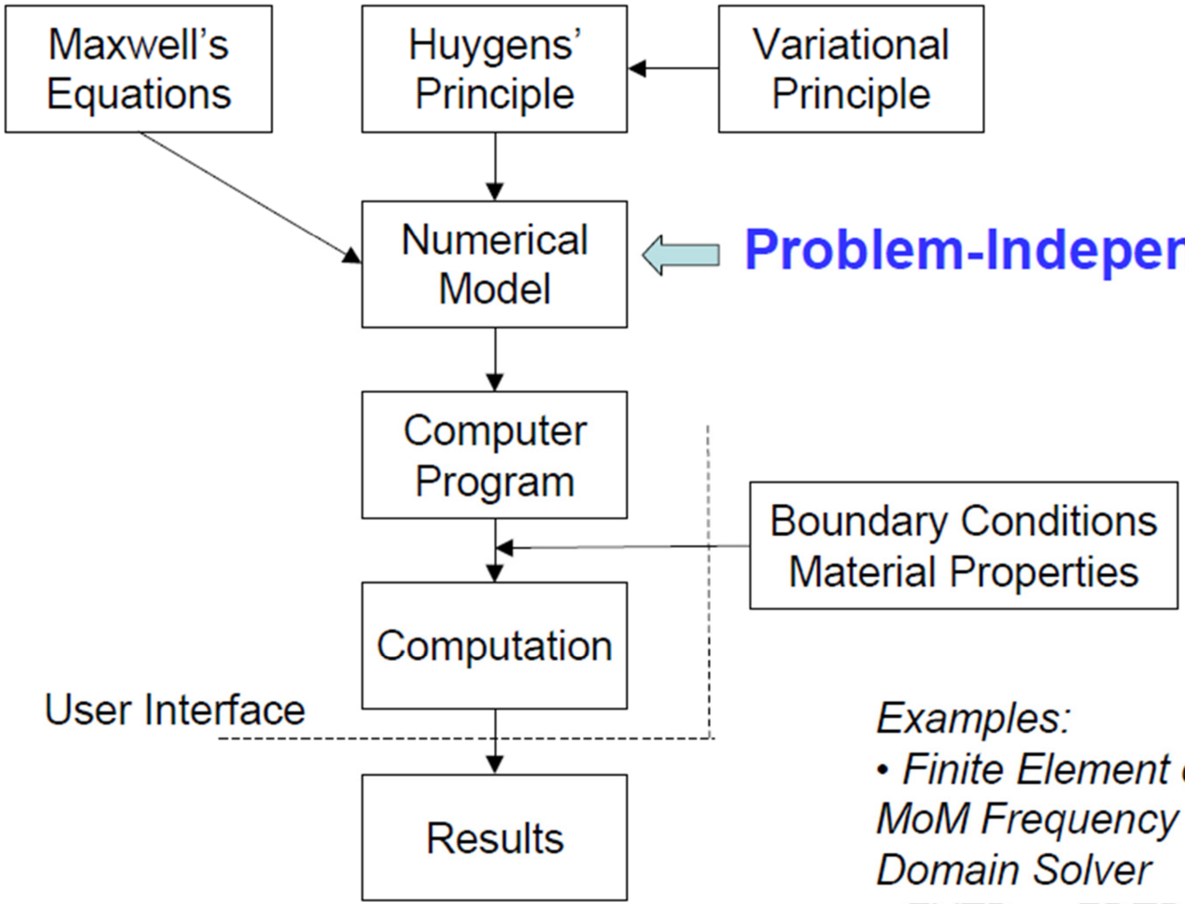


Examples:

- *Closed-form expressions for microstrip/transmission lines;*
- *Spectral domain program for coplanar waveguides;*
- Eigenvalue solvers for guided waves and cavities;

Modern Electromagnetic Solution

Numerical Formulation And Discretization



Maxwell's Equations

Huygens' Principle

Variational Principle

Numerical Model

Computer Program

Boundary Conditions Material Properties

Computation

User Interface

Results

Problem-Independent

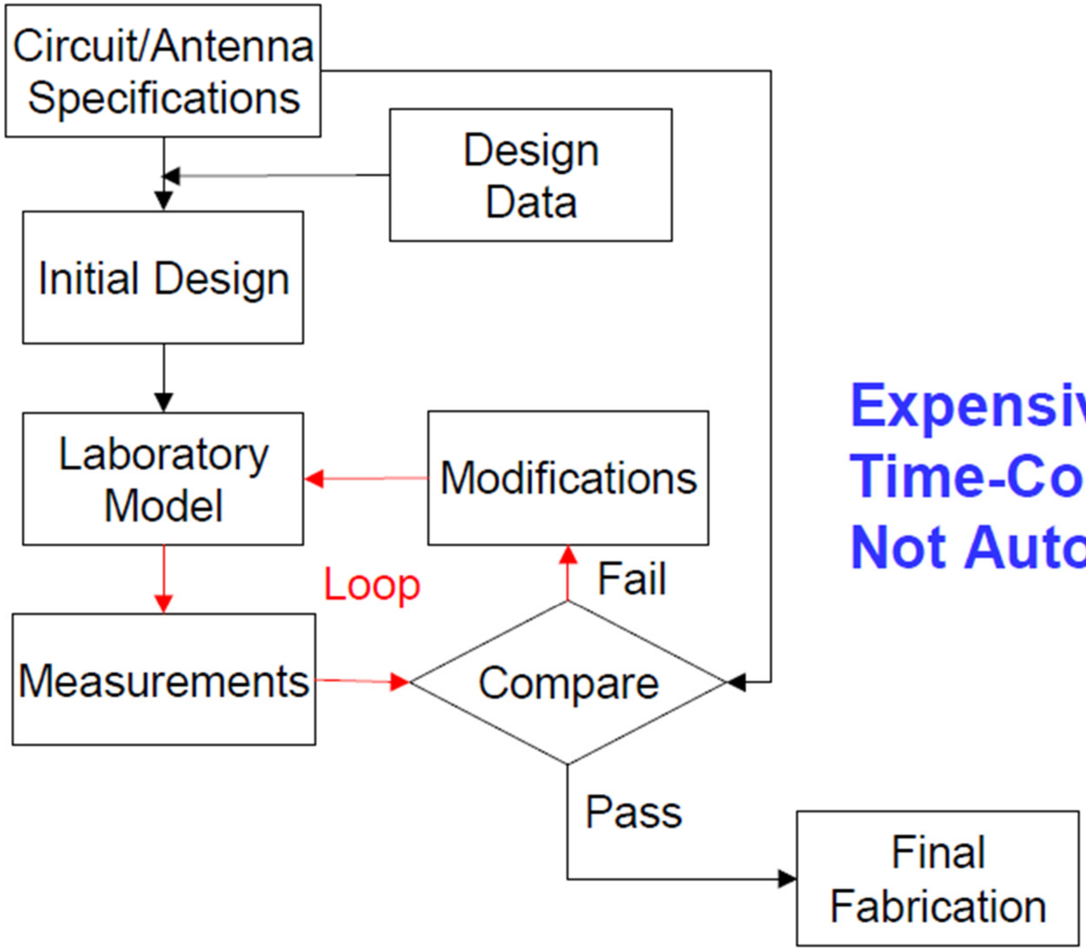
Postprocessing

Examples:

- *Finite Element or MoM Frequency Domain Solver*
- *FVTD or FDTD Time Domain Numerical Simulation*

Conventional Microwave Design

Rapid Prototyping



Circuit/Antenna Specifications

Design Data

Initial Design

Laboratory Model

Modifications

Loop

Fail

Measurements

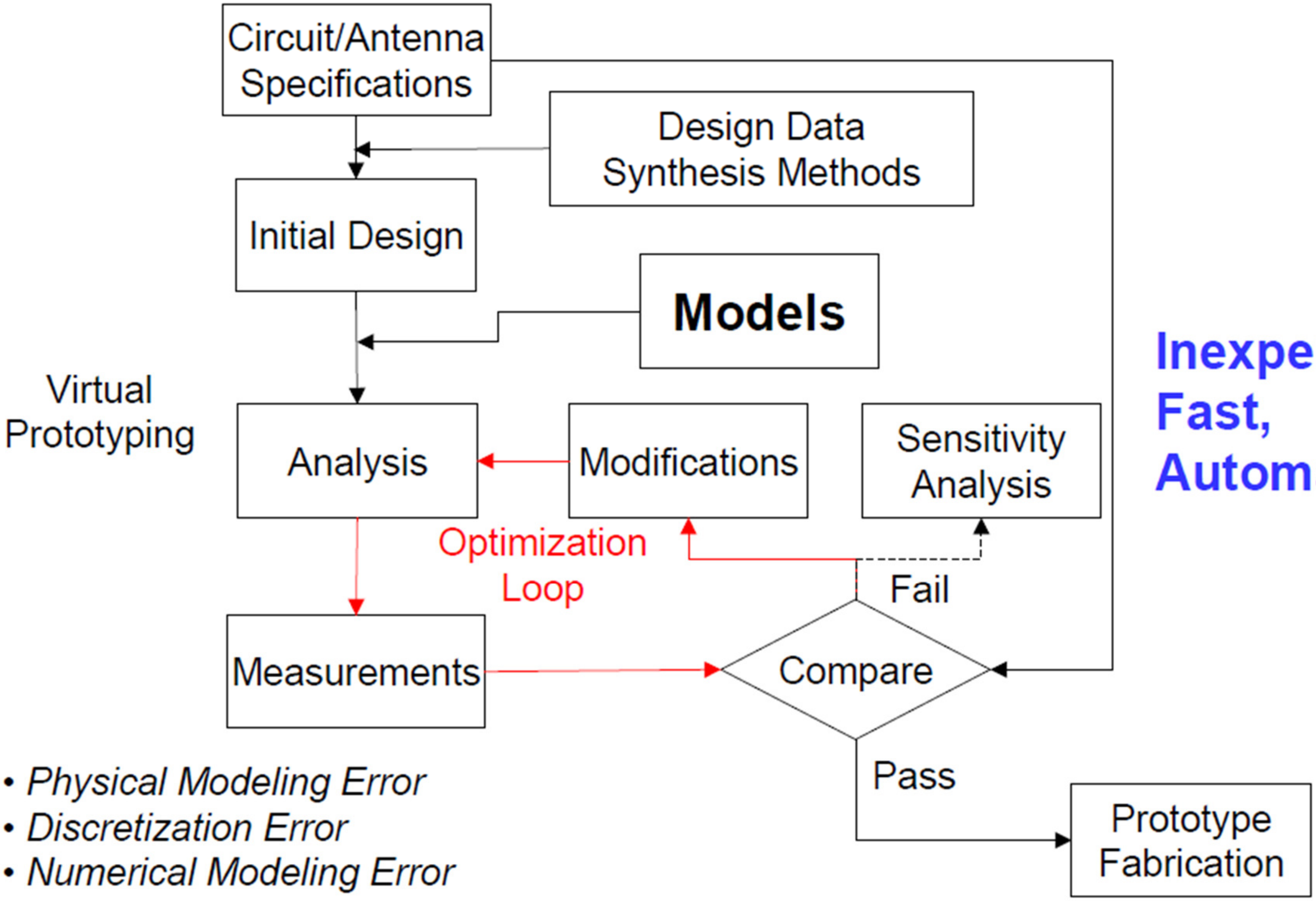
Compare

Pass

Final Fabrication

Expensive,
Time-Consuming
Not Automated

Computer-Aided Design (CAD)



Circuit/Antenna Specifications

Design Data Synthesis Methods

Initial Design

Models

Virtual Prototyping

Analysis

Modifications

Sensitivity Analysis

Optimization Loop

Fail

Measurements

Compare

Pass

Prototype Fabrication

Inexpensive,
Fast,
Automated

- *Physical Modeling Error*
- *Discretization Error*
- *Numerical Modeling Error*
- *Measurement Error*

Electromagnetic Simulators

- An Electromagnetic Simulator is a modeling tool that:
  - solves electromagnetic field problems by numerical analysis;
  - extracts engineering parameters from the field solution and visualize fields and parameters;
  - allows design by means of analysis combined with optimization (PSO, GA, parameterized models, etc.).
- The field solver engine employs one or several numerical methods obtained through the practice of CEM:
  - is the theory and practice of solving electromagnetic field problems on digital computers;
  - provides the only viable approach to solving "real world" field problems;
  - enables Computer-Aided Engineering (CAE) and Computer-Aided Design (CAD) of EM components and systems.

Solving EM Field Problems

- Find electromagnetic field and/or source functions such that they
  - obey Maxwell's equations,
  - satisfy all boundary conditions,
  - satisfy all interface and material conditions,
  - satisfy all excitation conditions.

(In both time and space, or at one frequency in space)

- Field solutions are then unique when tangential fields on conductors and initial conditions are known
- But numerical solution depends on
  - *Physical Modeling Error*
  - *Discretization Error*
  - *Numerical Modeling Error*
  - *Measurement Error*

Field-Solving Methods

Methods for solving Maxwell’s Equations:

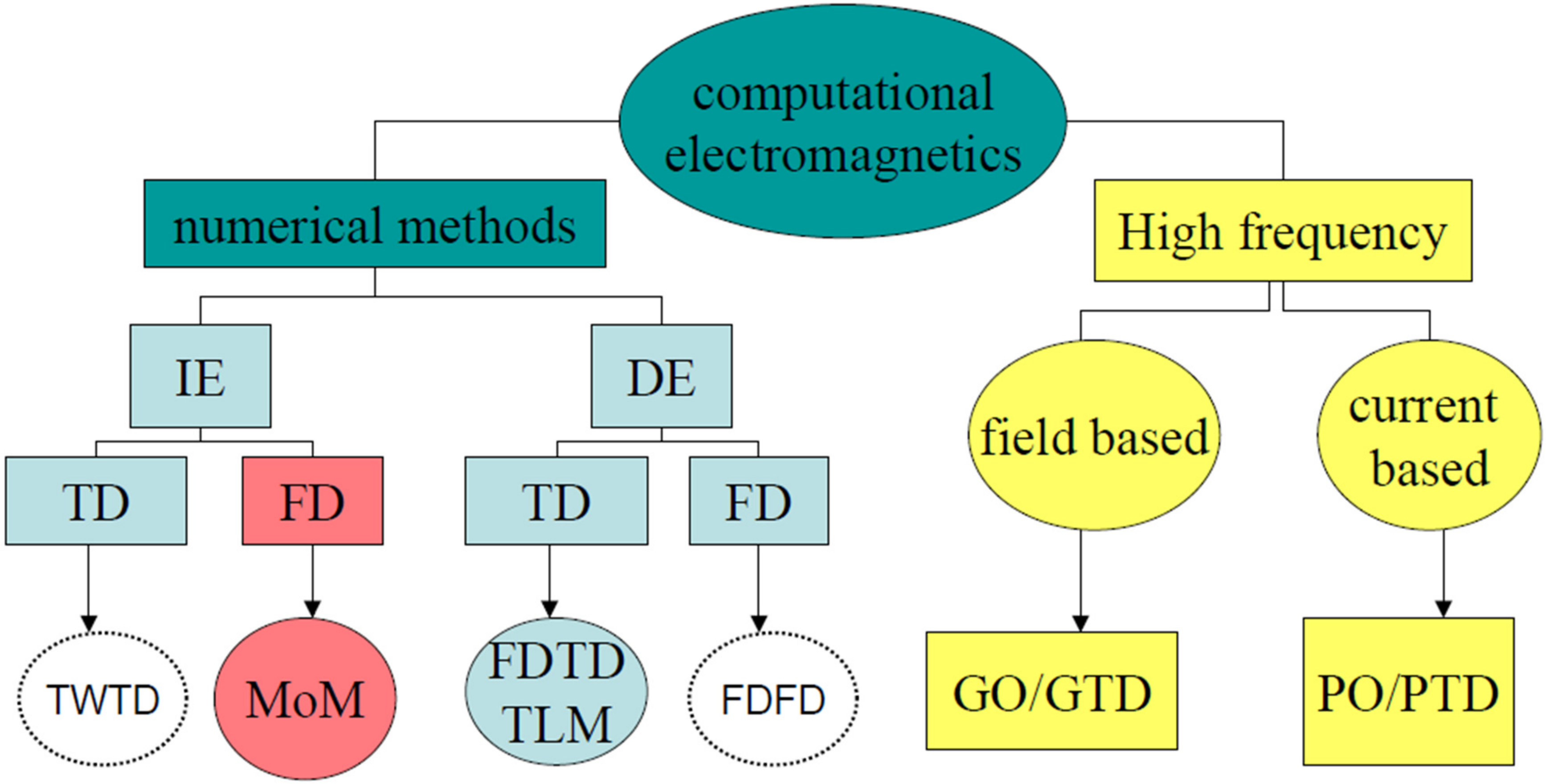
- Analytical Methods
  - Exact explicit solutions (only a few ideal cases)
- Semi-Analytical Methods
  - Explicit solutions requiring final numerical evaluation
  - Numerical solutions with analytical “preprocessing”
- Approximate analytical models
  - Approximate analytical solutions for simplified structures (provides physical insight)
  - Only practical way to handle very large electrical structures
- Numerical Methods
  - Differential or integral equations are transformed into matrix equations by numerical approximations (sampling) and solved iteratively or by matrix inversion

Overview of CEM

- Central to all CEM techniques is the idea of discretizing some unknown EM property, for example:
  - In MoM the surface current is typically used
  - In FE, the Electric Field
  - In FDTD, the Electric and Magnetic Field
- Meshing is used to subdivide a large geometry into a number of nonoverlapping subregions or elements, for example:
  - In two dimensional regions triangles maybe used
  - In three dimensional geometries a tetrahedral shape may be used
- Within each element, a simple functional dependence (basis functions) is assumed for the spatial variation of the unknown
- CEM is a modeling process and therefore a study in acceptable approximation and numerical solution

  In other words, CEM replaces a *real* field problem with an *approximate* one which causes physical (geometric) and numerical limitations that one must keep in mind

Computational Hierarchy



Classification of Methods

Frequency Domain Methods (Time-Harmonic)

Time Domain Methods (Transient)

Fourier Transform

- *This distinction is based more on human experience than on physical or mathematical considerations.*
- *The time dimension can be treated as a fourth dimension in Minkowski space in the form jct, where c is the speed of light.*
- The user requires knowledge of different methods to be able to choose the most suitable design tool and setup the calculation correctly.
- In the most general sense, solution methods can thus be classified according to the number of dimensions upon which the field and source functions depend.

Why Model In The Frequency Domain?

- Most microwave engineers are more familiar with FD concepts than with TD concepts
- Frequency domain simulations are steady-state
- Complex notation is elegant and efficient
- Specifications are traditionally formulated in the FD (S-Parameters, loss tangent, dispersion)
- Time domain information can be obtained by inverse Fourier Transform (Causality issues!)
- Dispersive materials and boundaries are easily described by frequency-dependent parameters

Why Model In The Time Domain?

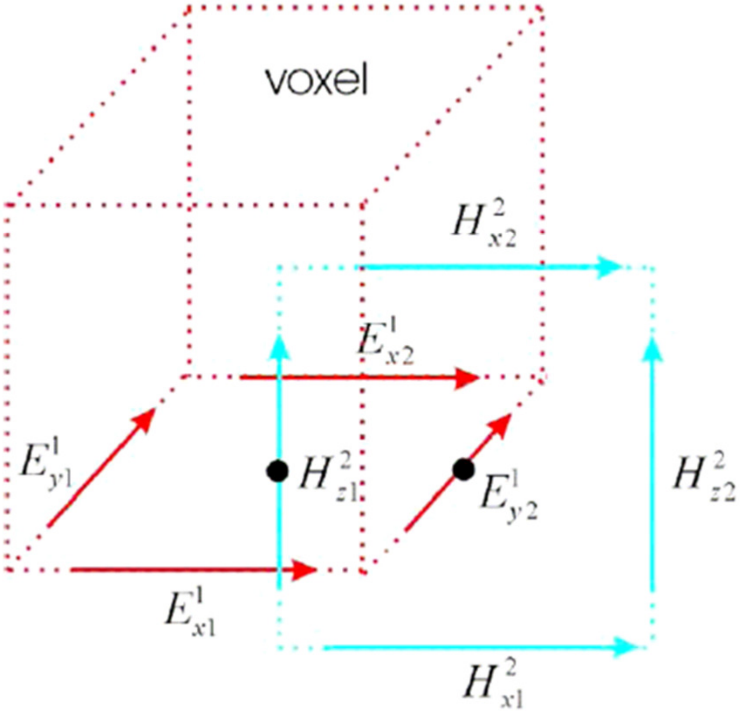
- Time domain simulations are “life-like” and allow visualization of signal propagation
- Virtual experiments are set up as in the lab (Source, reference planes, output probes)
- Cause and effect can be distinguished
- One simulation can cover a wide bandwidth
- Transient phenomena can be simulated
- Nonlinear behavior is modeled naturally
- Dispersive materials and boundaries are modeled in a more physical manner
- Frequency domain information can be obtained via Fourier transform

Finite Difference Time Domain (FDTD)

- **The whole simulation domain is discretized by using cubes (called *voxels*)**
  - Dielectric materials easy to model
  - Problems with arbitrary (e.g. round-shaped) objects

- **Time-domain method**
  - Good for broadband simulations
  - Low-loss resonant structures store energy, and simulation time is long

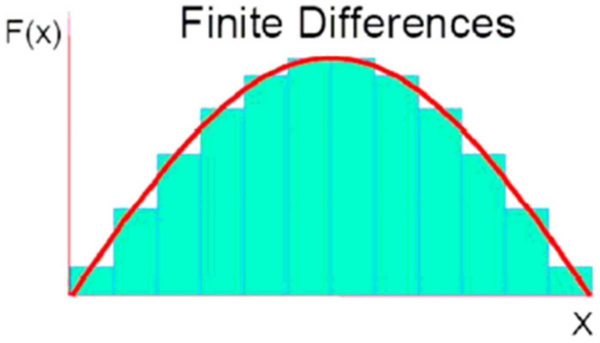
- **Popular FDTD-based simulators are *SEMCAD-X* by Speag and *Microwave Studio* by CST**



magnetic field component H^2_{z1} is calculated from the surrounding electric field components E^1_{x1}, E^1_{y1}, E^1_{x2} and E^1_{y1} by using discretized Maxwell's equations

Finite Difference Time Domain (FDTD)

- **Orthogonal geometry of cells**
- **Discretized Maxwell's equations**
- **Discretization leads to numerical dispersion**
- **Iterative calculation of field components in time domain**
- **Arbitrary material parameter distributions can be treated (problems with curved shapes)**
- **Low memory consumption – no need to solve linear equations with huge numbers of unknowns (but maybe long running time is needed)**



Comparison

	MoM	**FEM**	**FDTD**
Discretization	Only wires or surfaces	Entire domain (tetrahedron)	Entire domain (cube)
Solution method	FD, linear equations, full matrix	FD, linear equations, sparse matrix	TD, iterations
Boundary conditions	No need for special BC	Absorbing boundary conditions	Absorbing boundary conditions
Numerical effort	$\sim N^3$	$\sim N^2$	$\sim N$

Comparison

	MoM	FEM	FDTD
Well suited for:	Wire antennas, metal surfaces, coupling between distant elements, arbitrary shapes of surfaces, single or few frequencies	Arbitrary shapes and materials, single or few frequencies	Preferably orthogonal planar boundaries, arbitrary materials, broadband investigations
Not so well suited for:	Various materials, electrically very large structures, broadband investigations	Electrically large structures, coupling between distant elements, broadband investigations	Coupling between distant elements, high-Q structures

Maxwell's equations in Cartesian coordinates

Expanding $\vec{E}$ and $\vec{H}$ into the Cartesian components:

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x\right) \qquad \frac{\partial H_x}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} - \sigma^* H_x\right)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y\right) \qquad \frac{\partial H_y}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} - \sigma^* H_y\right)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z\right) \qquad \frac{\partial H_z}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} - \sigma^* H_z\right)$$

Note, only first order derivatives are needed.

The Yee Algorithm

Solving both E and H fields, in time and space.

- => Both E and H field boundaries can be used
- Solving both E and H fields => more robust
- =>Unique field features (e.g. singularities)

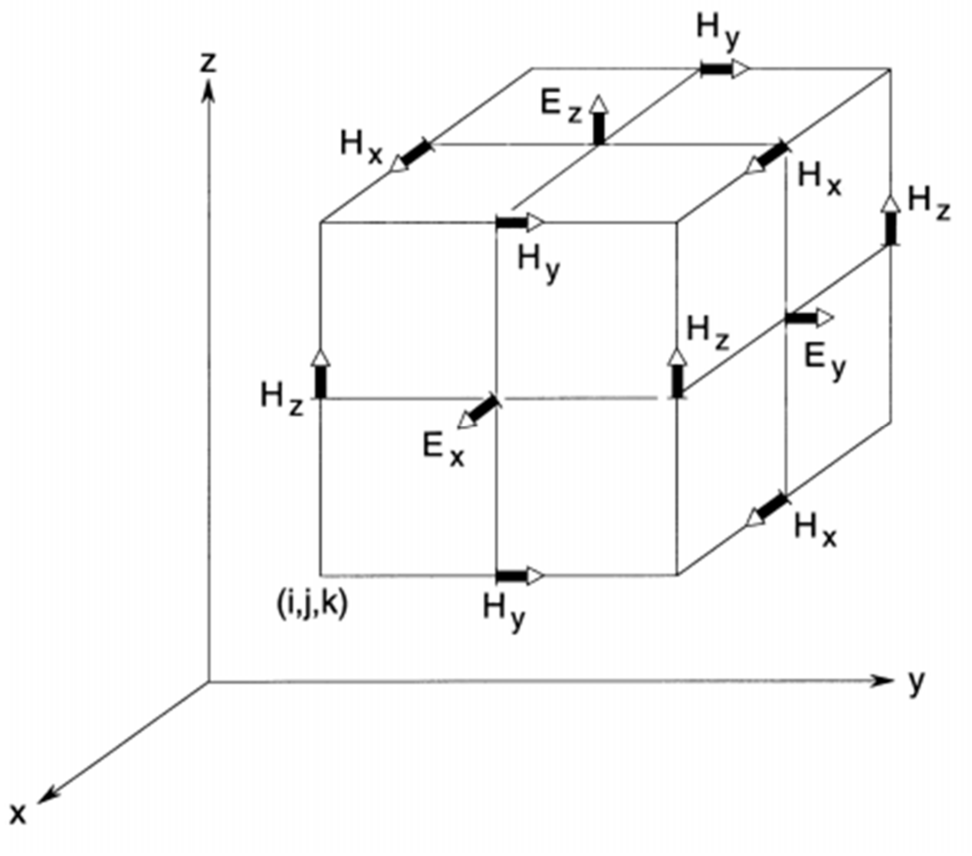
Yee Cell centres its E and H fields in 3D.

- FD expressions are central in nature and 2nd order accurate.
- Continuity of the tangential E and H fields across boundaries.
- Implicit enforce the two Gauss laws.

Yee Algorithm centres its E and H fields in time.

The Yee Cell

Yee Cell centres its E and H fields in 3D.



The Yee Time stepping

Yee Algorithm centres its E and H fields in time.

=> Time stepping is fully explicit.

FD expressions for the time derivatives are central in nature and 2nd order accurate.

Time stepping algorithm is nondissipative.

The Yee Notation

To keep the overview especially when considering 3D expressions Yee used the following notation which will be used for the FDTD equations.

$$u_X\left(i\Delta x,\ j\Delta y, k\Delta z, n\Delta t\right) = u^{n}_{X_{i,j,k}}$$

$$\frac{\partial u_X}{\partial x} \cong \frac{u^{n}_{X_{i+\frac{1}{2},j,k}} - u^{n}_{X_{i-\frac{1}{2},j,k}}}{\Delta x} + O\left[\left(\Delta x\right)^2\right]$$

Stability 2D and 3D

Using same procedure as for the 1D case we obtain:

$$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}}} \qquad \Delta t \leq \frac{1}{c\sqrt{\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}+\frac{1}{(\Delta z)^2}}}$$

For the case with equal spatial sampling:

$$\Delta t \leq \frac{\Delta s}{c\sqrt{2}} \qquad \Delta t \leq \frac{\Delta s}{c\sqrt{3}}$$

ABC (Absorbing boundary conditions)

Many geometries of interest are defined in “open” regions where the spatial domain of the computed field is unbounded in one or more coordinate directions.

No computer can store an infinite amount of data!

A suitable boundary condition on the outer perimeter of the domain Ω must be used to simulate its extension to infinity.

ABC (Absorbing boundary conditions)

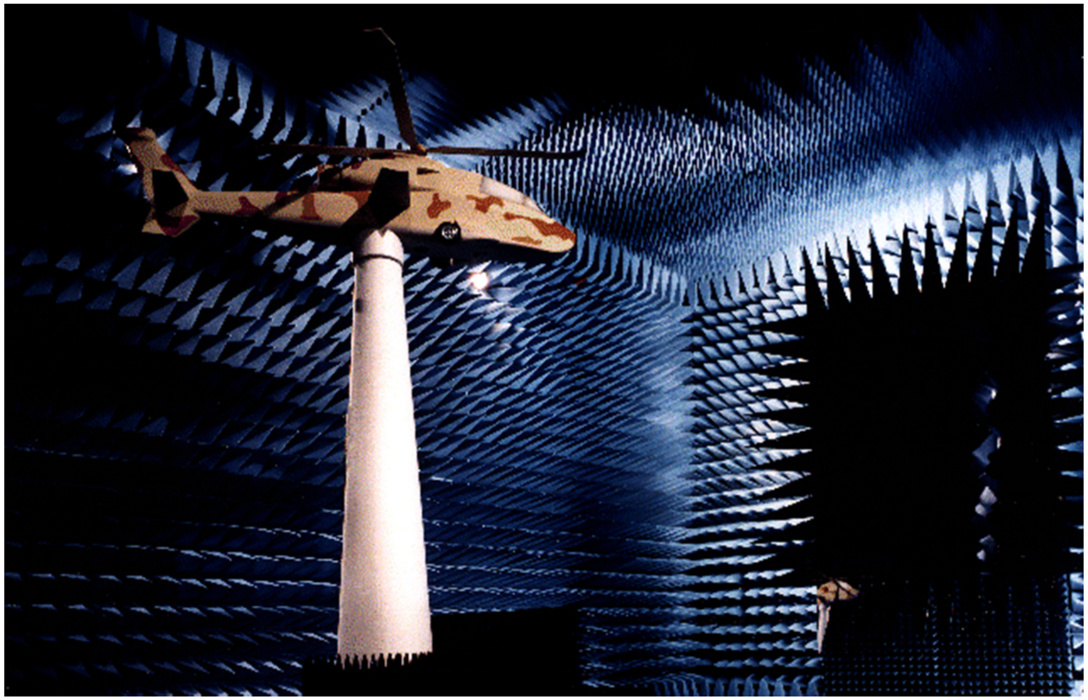
We need a boundary condition that permits all outward propagating numerical waves to exit Ω as if the simulation were performed on a computational domain of infinite extent.

We must suppress spurious reflections of the outgoing numerical waves to an acceptable level.

PML (Perfectly Matched Layer) ABC

We terminate the outer boundary of the space lattice in an absorbing material medium.

This is analogous to the physical treatment of the walls of an anechoic chamber.



PML (Perfectly Matched Layer) ABC

The innovation of Berenger's PML is that plane waves of arbitrary incidence, polarization, and frequency are matched at the boundary.

A novel split-field formulation of Maxwell's equations is derived.

By choosing loss parameters consistent with a dispersionless medium, a perfectly matched planar interface is derived.

Summary and Conclusions

- Numerical Methods allow us to solve real life EM problems (within certain limits). They form the engine(s) of electromagnetic simulators.
- Electromagnetic simulators are not merely Maxwell equation solvers, but powerful simulation and design tools with visualization capabilities.
- Understanding EM phenomena and knowledge of radio engineering are necessary for successful use of codes.
- Understanding the underlying numerical methods is essential in assessing the accuracy, performance and limitations of a particular simulation tool.
- Electromagnetic simulators are the heart of modern CAD tools for analog microwave, digital high-speed and mixed signal design, EMC and signal integrity engineering and other applications of electromagnetic fields and waves.