A field solvers view on constructing compact models for devices in an electromagnetic ambient

Wim Schoenmaker – MAGWEL

Nick van der Meijs – TU Delft

Daniel Ioan – Polytechnical University Bucharest

Overview

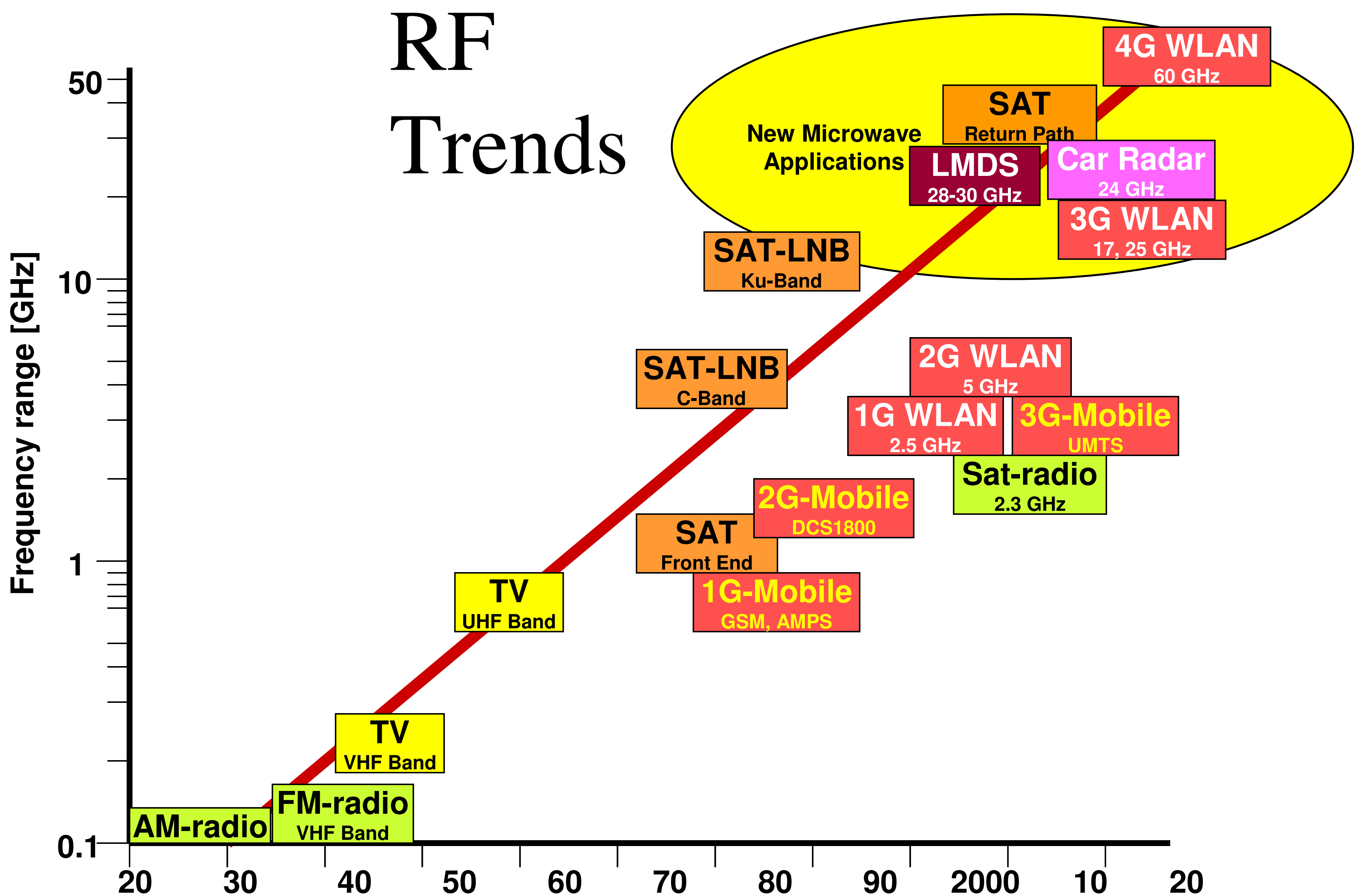
- Introduction
- Field solvers
- Field solver view on devices
- Ambient effects
- Devices and EM ambient
- Conclusions

Introduction

- After the RF applications now the µ-wave and mm-wave applications will be integrated on silicon
- CMOS will start dominating in RF and will slowly take up in µ/mm-wave applications and so trigger here also the integration trend
- EM tools are needed to understand/analyze the complex behavior of circuits, especially where Kirchhoff's laws will start deviating from reality

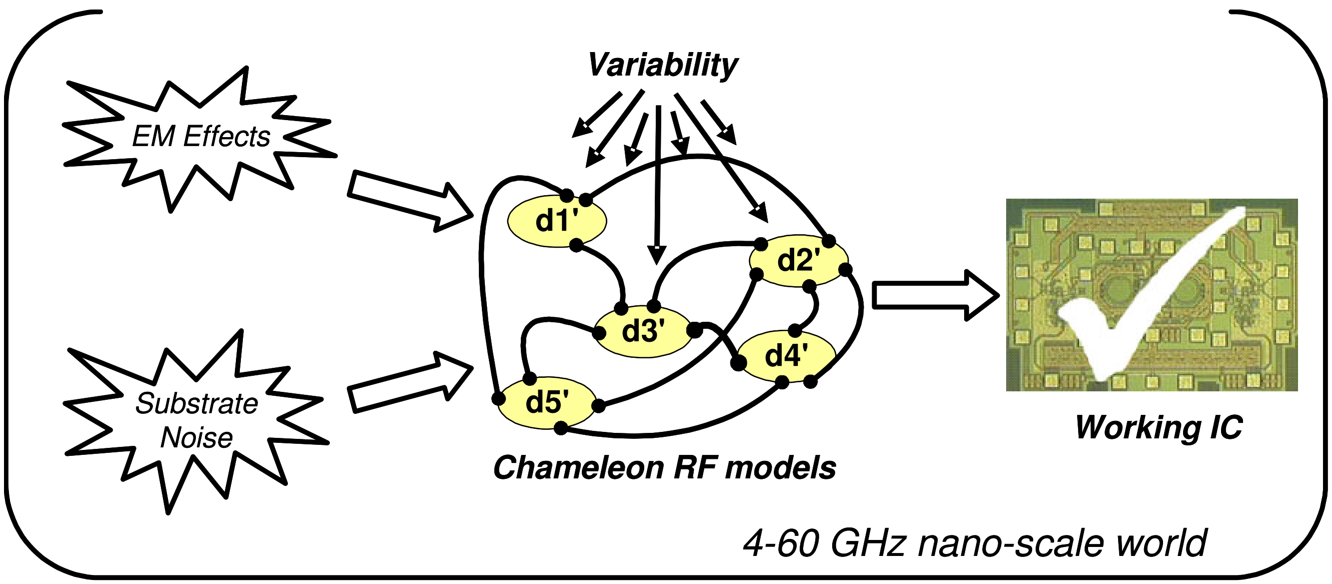
Courtesy: Domique Leenaerts (PHILIPS)

Introduction



Introduction

- CHAMELEON-RF   EU project
- device characterisation and environment influences
- tools for a thorough and accurate post-design verification



Introduction

- **CHAMELEON-RF work flow**
  - electromagnetic field aspects of coupling, at the component level.
  - coupling of the front-end (active devices) with back-end
  - refinement of compact models will be refined with ‘hooks’ or connectors that allow the incorporation of induced field effects
  - Reduced-order modelling (ROM) of the SPICE net lists
  - Inclusion of variability in the ROM
  - Design, processing, characterization of test devices
  - Validation

Introduction

- Example: Effects of integrated passives on transistors
- Problem definition:
  - *Integrated passive component inject high-frequency electric fields into active devices.*
- Open issue:
  - *How does this modify the operation of the active devices ?*
- Use field solvers to address this problem

Field Solvers

Architecture:

- Start from the 'fundamental' equations of physics
  - Maxwell equations
  - Drift-diffusion equation (or variation thereof)
  - Ohm's law
  - Models for the material parameters
- Output
  - Current and voltages at contacts
  - S-parameters
  - 'Inside looks' e.g. field intensities, current densities

numerical approach

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{D} = \varepsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$-\nabla \cdot (\varepsilon \nabla V + j\omega \mathbf{A}) = \rho$$

$$\nabla \times \nabla \times \mathbf{A} = \mu \mathbf{J} - j\omega\mu\varepsilon(\nabla V + j\omega \mathbf{A})$$

- Connection with Kirchhoff's laws through V variables

numerical approach

Semi-conductors

$$\nabla \cdot \mathbf{j}_n - q\, j\omega\, n = U(n,p)$$
$$\nabla \cdot \mathbf{j}_p + q\, j\omega\, p = -U(n,p)$$

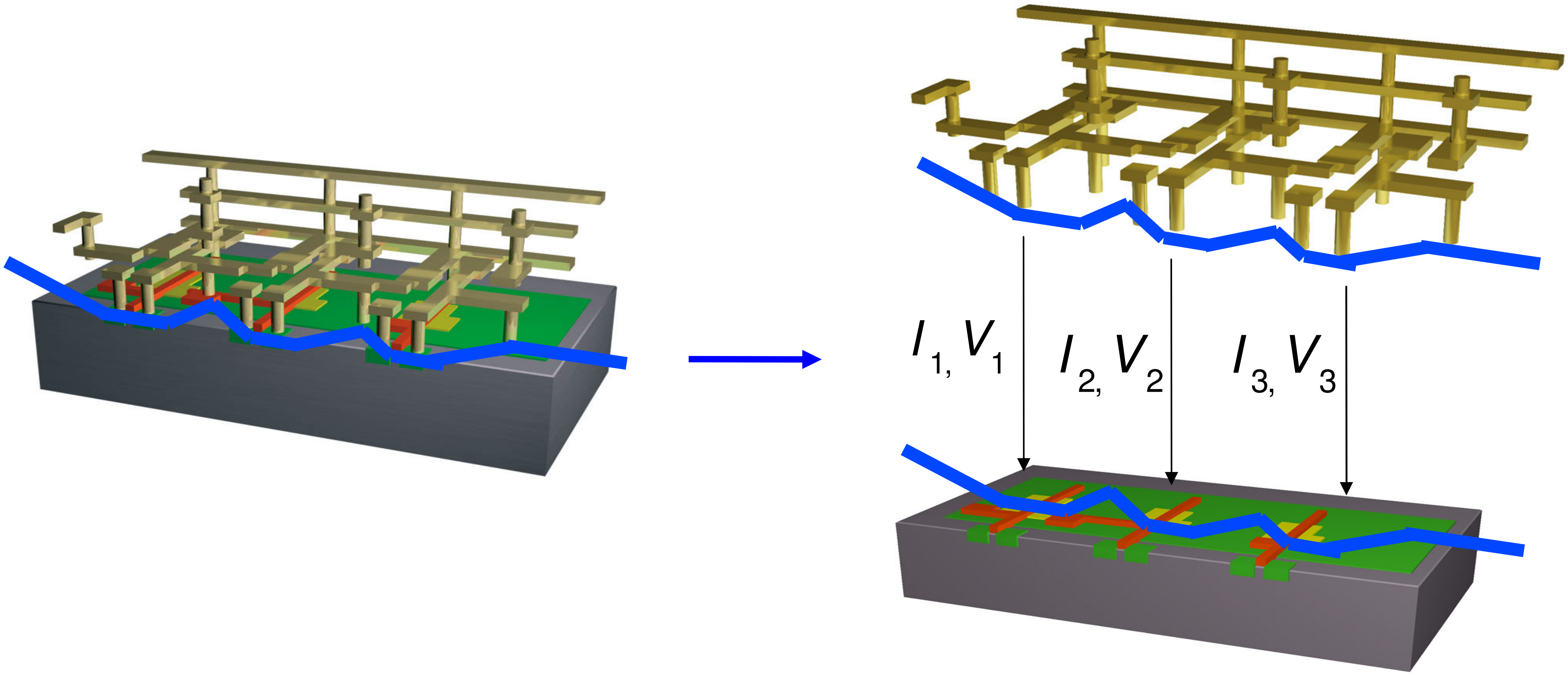
$$\rho = q(p - n + N_D - N_A)$$
$$\mathbf{j}_n = q\mu_n n\mathbf{E} + kT\mu_n \nabla n$$
$$\mathbf{j}_n = q\mu_p p\mathbf{E} - kT\mu_p \nabla p$$
$$\mathbf{j} = \mathbf{j}_n + \mathbf{j}_p$$

Conductors

$$\nabla \cdot \mathbf{j} = -j\omega\rho$$
$$\mathbf{j} = \sigma\, \mathbf{E}$$

- Back-end (‘on’silicon) and Front-end (‘in’ silicon) issues can now be addressed in one environment

Decoupled in- and on-Silicon simulation



Reduce interaction between in- and on-Silicon part to currents and voltages at contacts. And use a different simulator for each part.

Some considerations

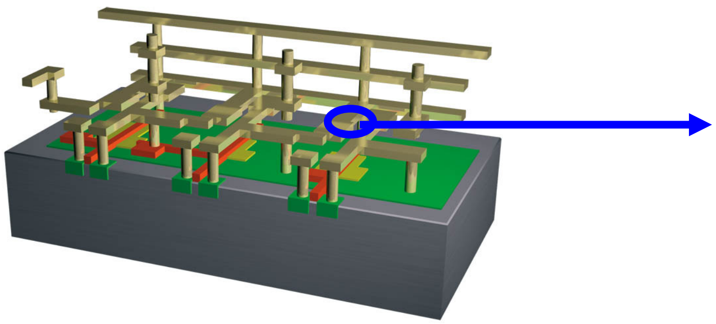
- At high frequencies: $|\nabla V| \approx |\omega \mathbf{A}|$
- Skin effect: $\mathbf{E} \approx 0$ because both terms cancel
- Serious induction **E**-fields are injected
- These fields are superimposed on the **E**- fields of the contact bias conditions
- Electromagnetic TCAD studies structures under 'RF' conditions

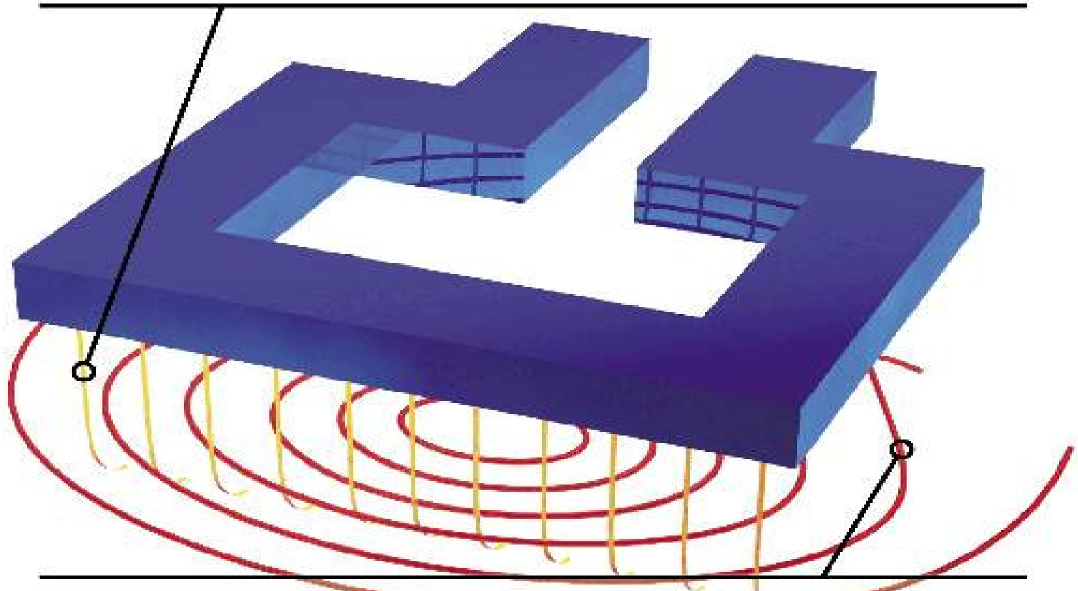
Some considerations

The link with Kirchhoff:

- Currents(In) = Current(Out)
  - This is not evident for finite-element implementations
  - Finite-volume integration implementations respect this requirements (MAGWEL)
- *Three* kinds of materials are encountered in a simulation set-up
  - Highly non-trivial interface conditions!

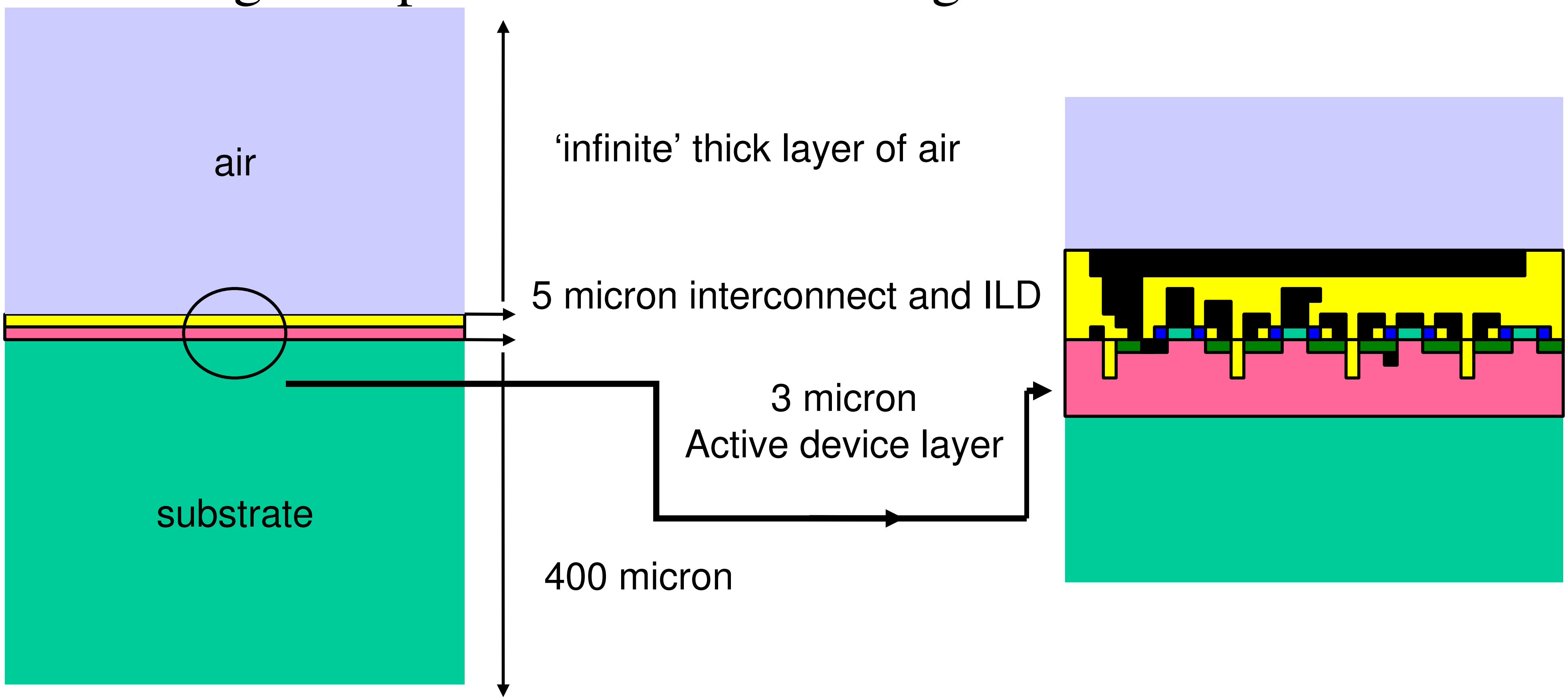
Two types of EM effects





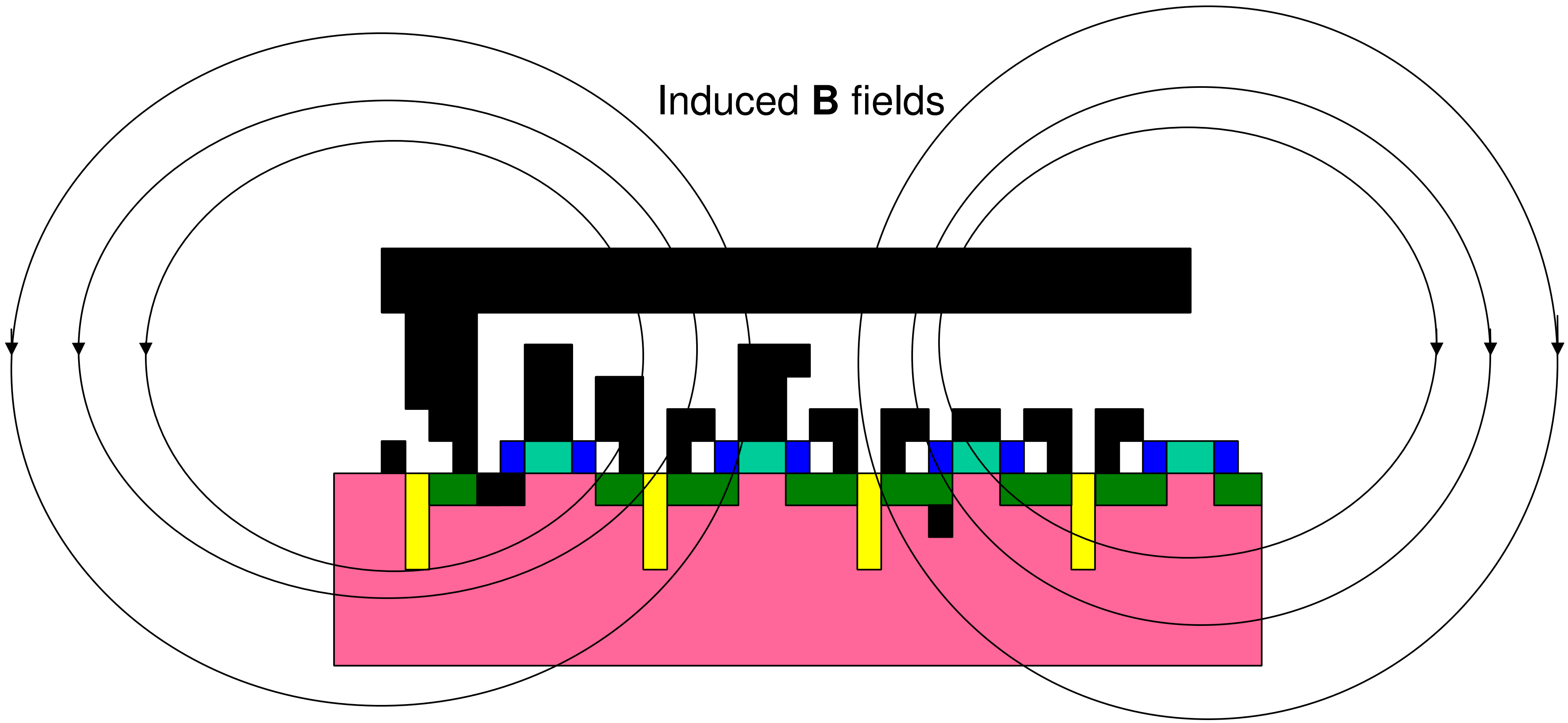
Active and passive structures

- Situation of the problem
  - Different scales under consideration
  - Integrated passive devices >> single active devices



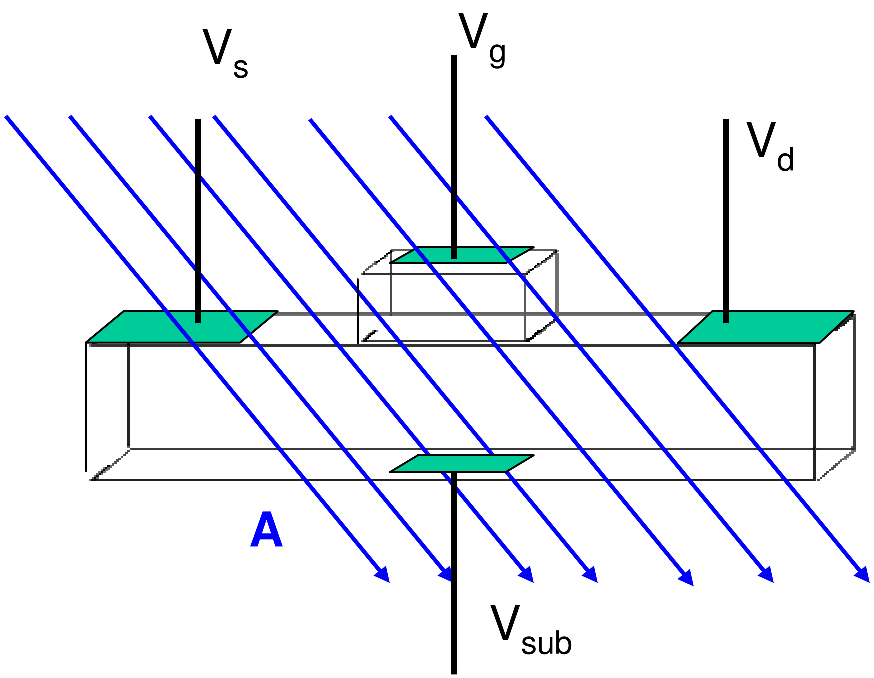
Field solver's approach

- The passive device injects a vector potential in the active device of which the magnitude and director can be taken ***constant*** over the device dimensions



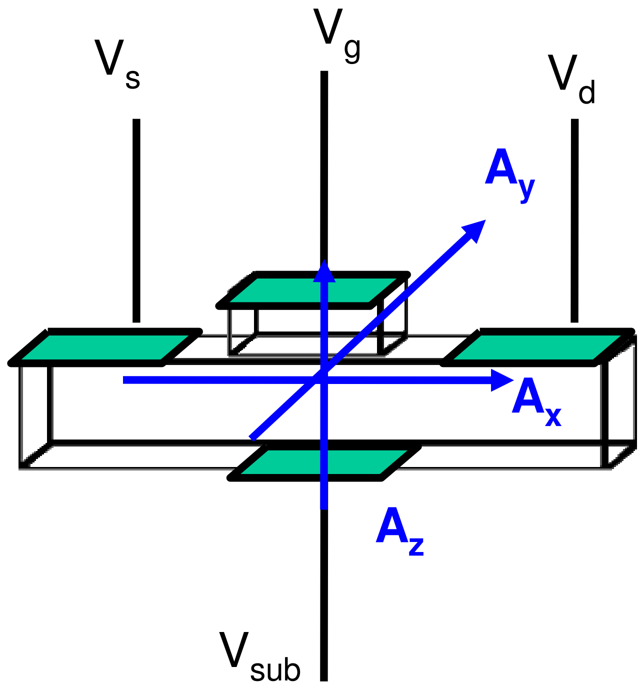
Field solver's approach

- A transistor now senses also an external **A** vector
- RF Transistor modeling
  - Voltages at the gate, source, drain and substrate
  - External vector field through the transistor
  - Electric field in the transistor: $\mathbf{E} = -\nabla V - j\omega\,\mathbf{A}$



MAGWEL's proposed approach

- The **A** field has 3 components:
  - A_x changes V_{ds} : $V_{ds} \rightarrow V_{ds} + j\omega\mathbf{A} . \Delta\mathbf{x} = \mathbf{V}_{ds}^{eff}$
  - A_z changes $V_{g,sub}$: $V_{g,sub} \rightarrow V_{g,sub} + j\omega\mathbf{A} . \Delta\mathbf{z} = \mathbf{V}_{g,sub}^{eff}$
  - The vector potential moves the transistor state in the IV plots
  - Move fully imaginary



Proposed method

Consider electric field in the channel from source to drain :

$$\int_{source}^{drain} \mathbf{dx}\cdot\mathbf{E} = -\int_{source}^{drain} \nabla V - j\omega \int_{source}^{drain} \mathbf{dx}\cdot\mathbf{A}$$

$$V_{ds} = \int_{source}^{drain} \mathbf{dx}\cdot\mathbf{E} - j\omega \int_{source}^{drain} \mathbf{dx}\cdot\mathbf{A}$$

$$V_{ds} + j\omega L_{ds} A_x(\mathbf{r}) = \int_{source}^{drain} \mathbf{dx}\cdot\mathbf{E}$$

An environment variable is found: $V_{ds}^{hook} = j\omega L_{ds} A_x(\mathbf{r})$

Refinements to the proposal

- 'Subtle' detail:
  - A constant vector potential can not generate a magnetic field

Approximation of the magnetic field

- Zero order approximation:

$$\mathbf{A}(\mathbf{r}) \cong \mathbf{A}(\mathbf{r}_0) \Longrightarrow \mathbf{B}=0, \quad V = V + j\omega \int_c \mathbf{A}d\mathbf{r}$$

- First order approximation:

$$\mathbf{A}(\mathbf{r}) \cong \mathbf{A}(\mathbf{r}_0) + \left.\frac{d\mathbf{A}}{d\mathbf{r}}\right|_{\mathbf{r}_0} (\mathbf{r}-\mathbf{r}_0) \Longrightarrow \mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A} \quad \text{constant}$$

- Higher order approximation:

$$\mathbf{A}(\mathbf{r}) \cong \mathbf{A}(\mathbf{r}_0) + \left.\frac{d\mathbf{A}}{d\mathbf{r}}\right|_{\mathbf{r}_0} (\mathbf{r}-\mathbf{r}_0) + \ldots\ldots \Longrightarrow \mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A}$$

Refinement

- Model refinement:
  - In order to include the effect of magnetic induction in active devices a linearly-varying vector potential must be taken

$$B_i = \varepsilon_{ijk} \frac{\partial A_i}{\partial x_j}$$

Model refinement

- When are magnetic fields important ?
  - If the Lorentz force law matters

$$\mathbf{E} \rightarrow \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

$$\mathbf{J} = \sigma(\mathbf{E} + \frac{\mathbf{J}}{q\rho} \times \mathbf{B}) = \sigma\mathbf{E} + \mu\mathbf{J} \times \mathbf{B}$$

metal

$$\mathbf{J}_p = \mu_p qp\mathbf{E} - qD_p \nabla p + qp\mathbf{v}_p \times \mathbf{B}$$

$$\mathbf{J}_n = \mu_p qp\mathbf{E} + qD_n \nabla n - qn\mathbf{v}_n \times \mathbf{B}$$

$$\mathbf{v}_p = \frac{\mathbf{J}_p}{qp}$$

$$\mathbf{v}_n = -\frac{\mathbf{J}_n}{qn}$$

} semiconductor

Model refinements

- Solve the implicitly given currents

$$\begin{bmatrix} 1 & -\mu B_z & \mu B_y \\ \mu B_z & 1 & \mu B_x \\ -\mu B_y & \mu B_x & 1 \end{bmatrix} \begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \begin{bmatrix} \sigma E_x \\ \sigma E_y \\ \sigma E_z \end{bmatrix}$$

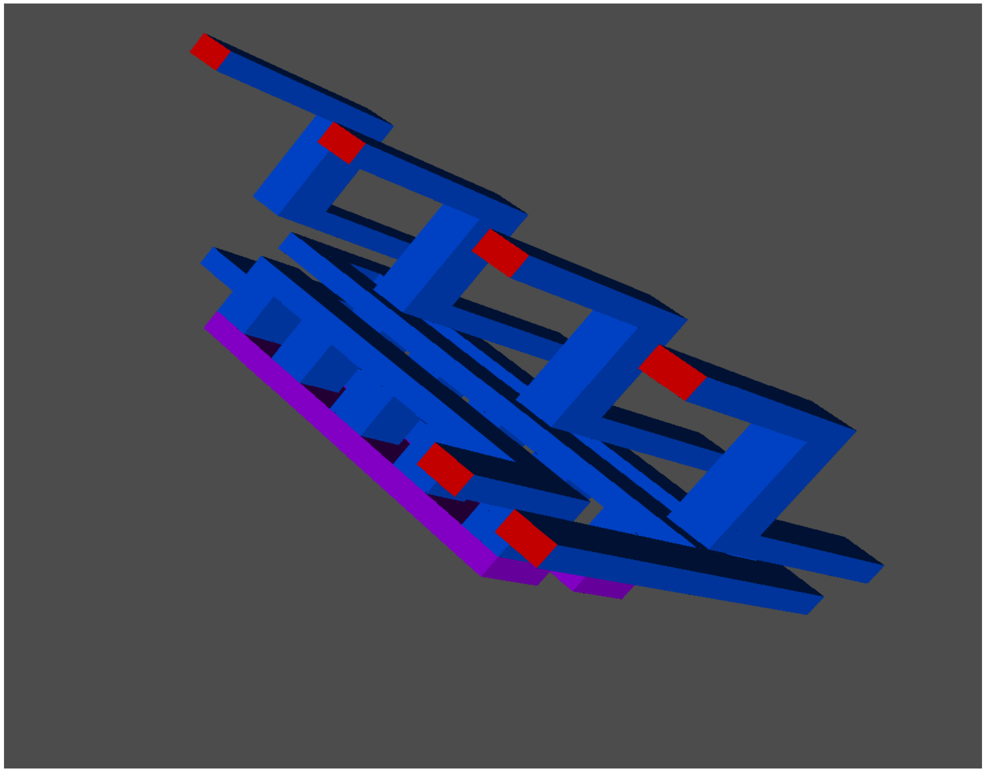
$$\mathbf{J} = \frac{1}{1+\mu^2 B^2}\left(\sigma\mathbf{E} + \mu\sigma\mathbf{E}\times\mathbf{B} + \mu^2\sigma(\mathbf{E}\cdot\mathbf{B})\mathbf{B} \right)$$

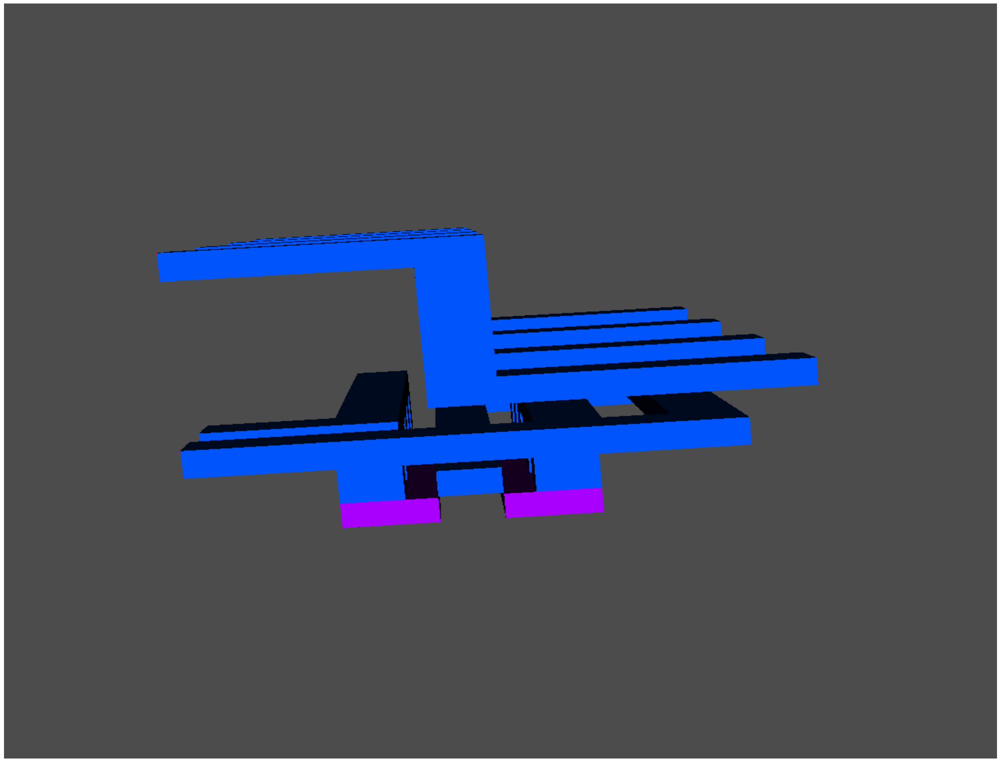
$$\mu B \ll 1 \quad \Rightarrow \quad \mathbf{J} = \sigma\left(\mathbf{E} + \mu\,\mathbf{E}\times\mathbf{B}\right)$$

- This equation can be used to explore influence of $\mathbf{B}$

RF MOS transistor

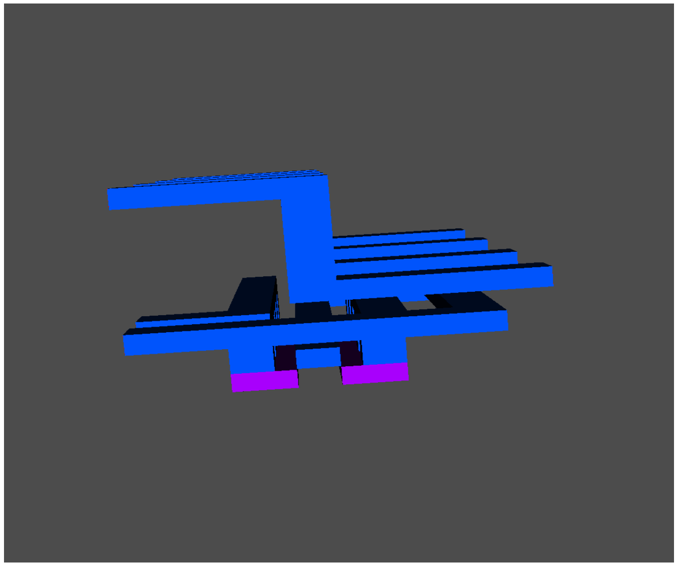
Calculate s-parameters of transistor and attached interconnect at once

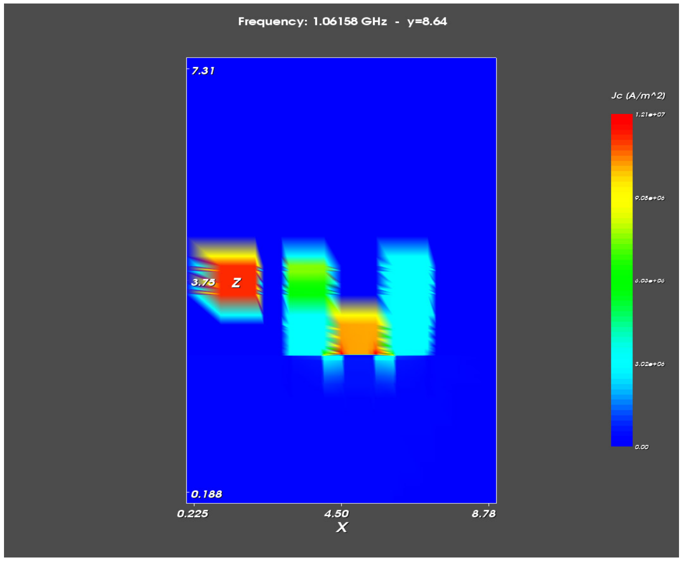


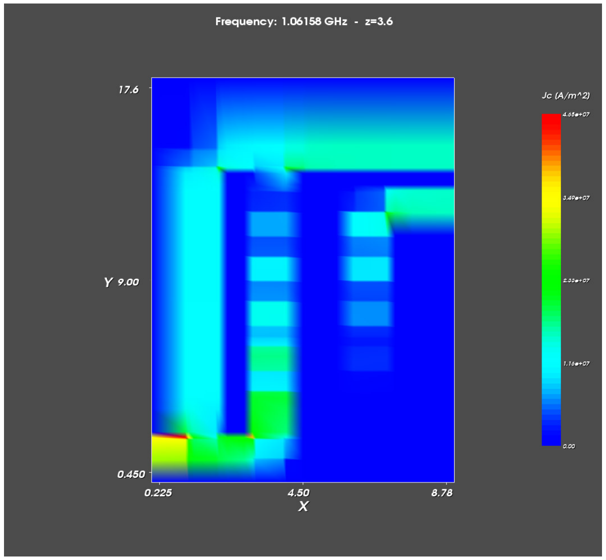


RF MOS transistor

Visual inspection of currents in structure

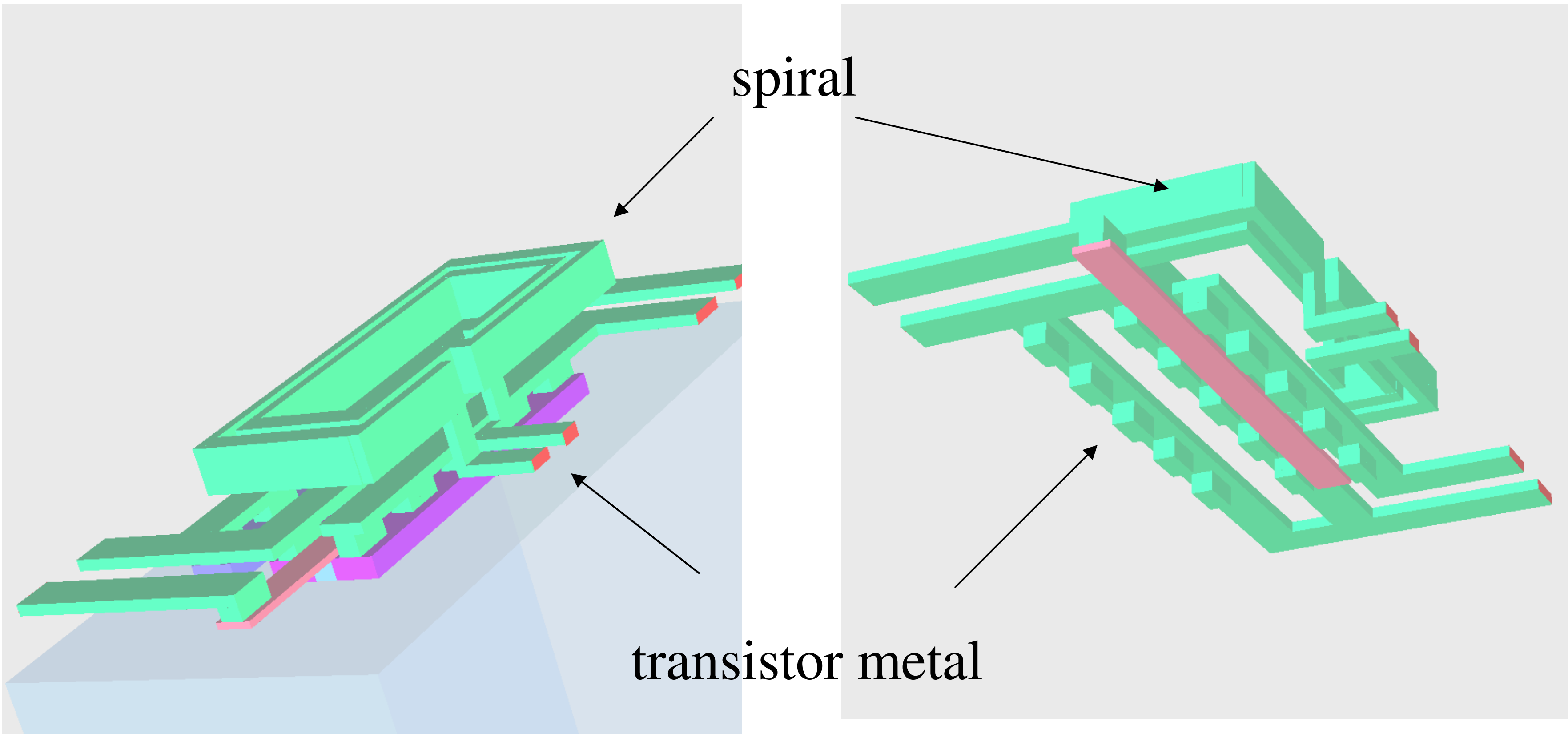






Second case under study

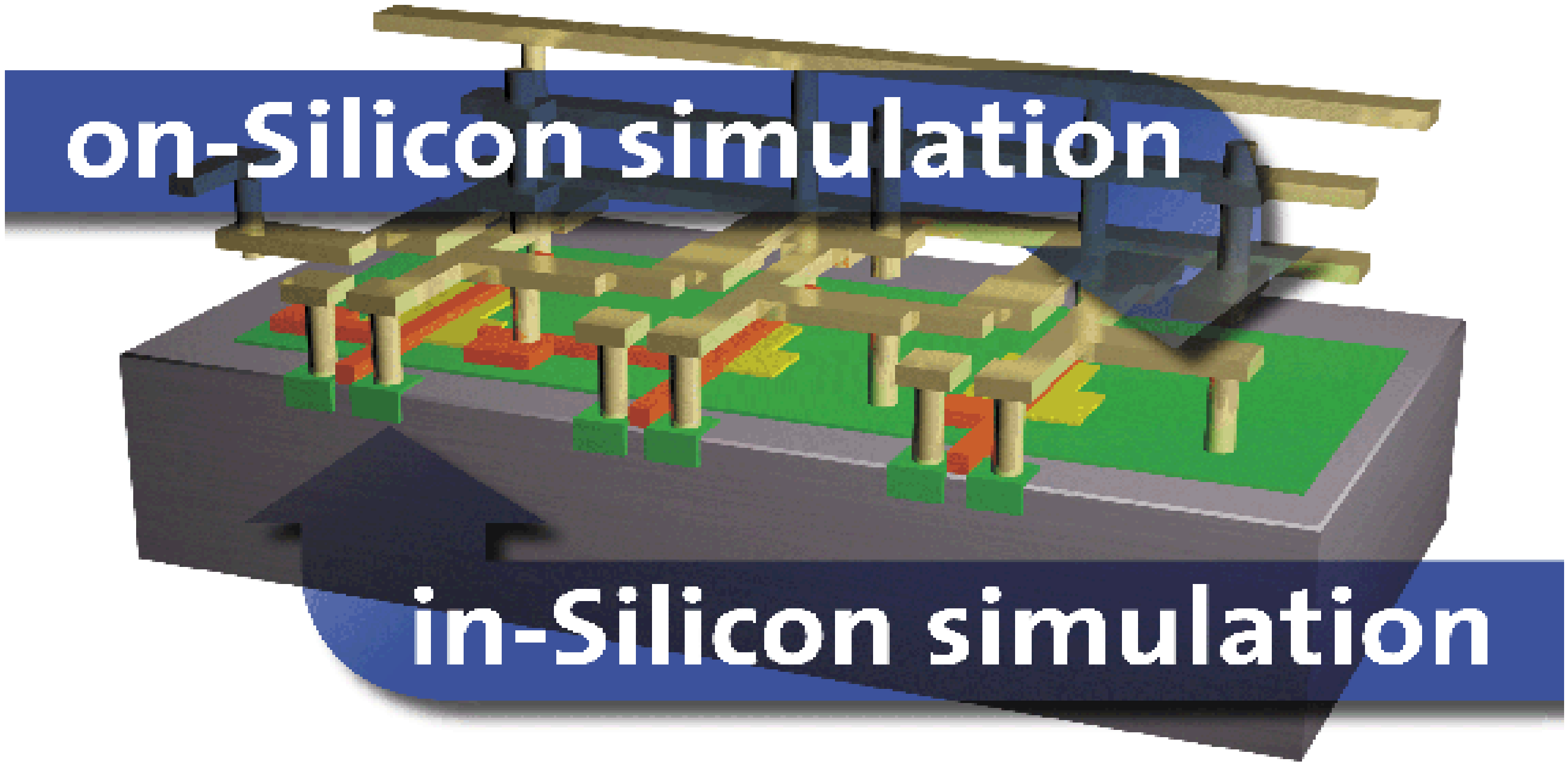
- Local inductor above the transistor



Conclusions

- An on set is made to view that devices are not only controlled by their port conditions, but:
- Generic injections are translated to port conditions
- Simulation studies can be performed by tools by which fields from in-chip ‘aggressor’ passives can be injected into ‘victim’ devices
- For further details see: *www.magwel.com*

Thank You !



Support from EU is gratefully acknowledged:
Codestar, nanoCMOS, Chameleon-RF, PULLNANO

