Quantum
Mechanical &
Electromagnetic
Systems
Modelling Lab

Broadband Boundary Integral Equation Modelling for Signal Integrity and EMC Assessment

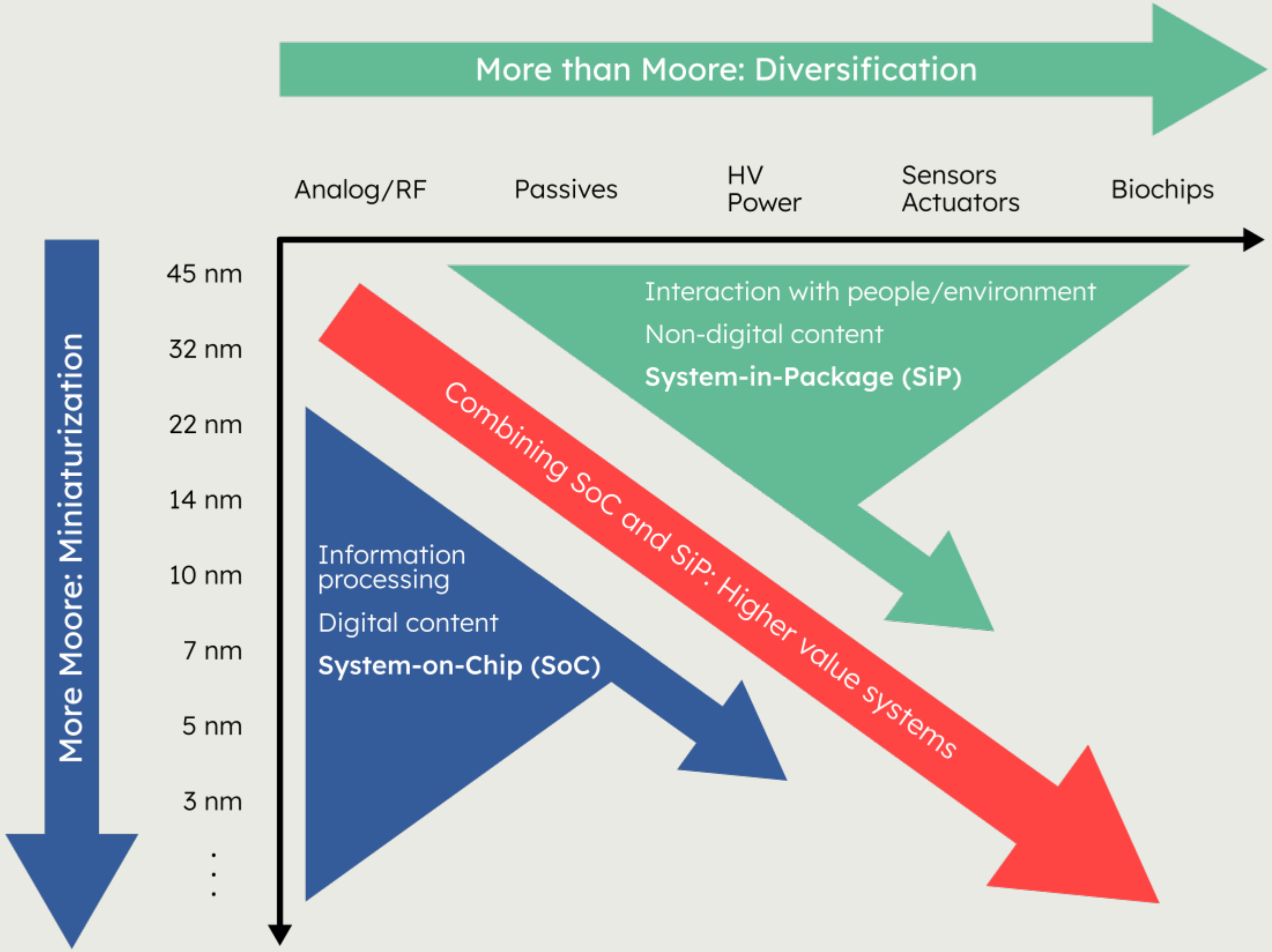
Martijn Huynen, Dries Vande Ginste

quest.

EMC Forum

Research context at quest

Roadmap for semiconductors.



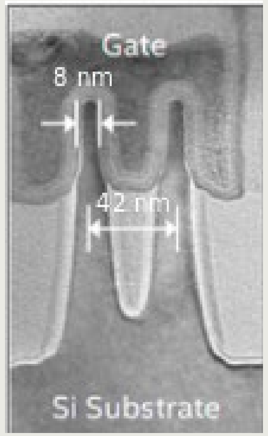
Research context at quest

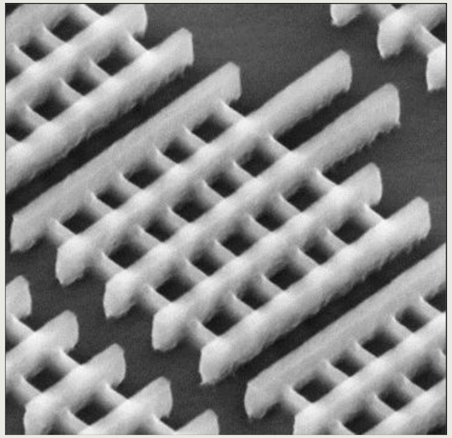
Moore, Moorer, Moorest.

Modeling challenges

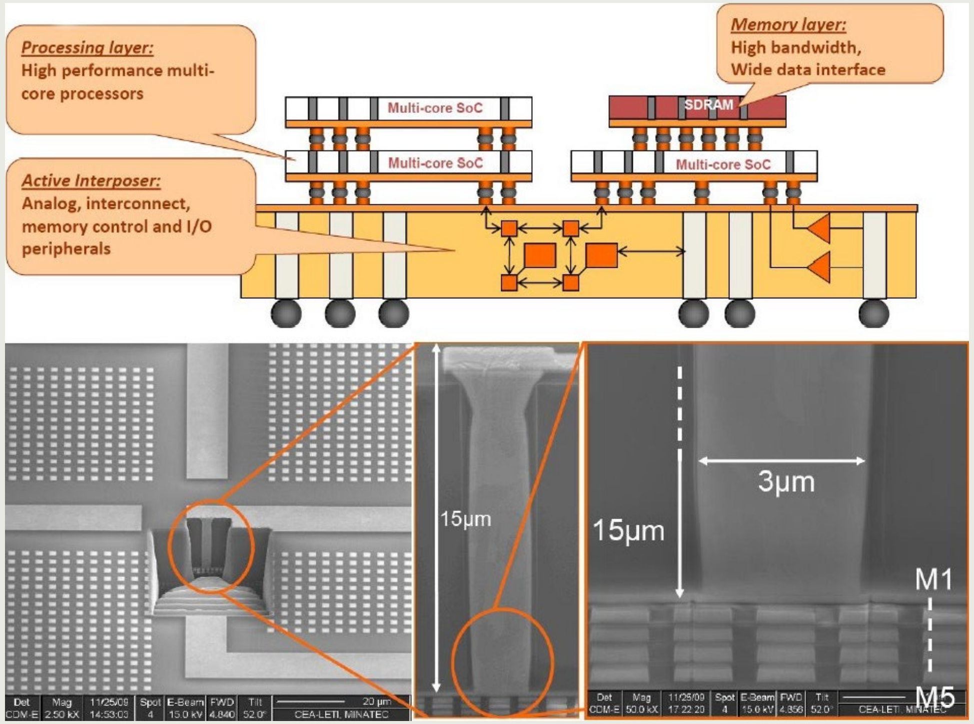
- Electromagnetic (EM) full -wave
- Heterogeneity
- Highly multiscale

example 1: Intel's Core i7-8700K processor with tri-gate transistor technology





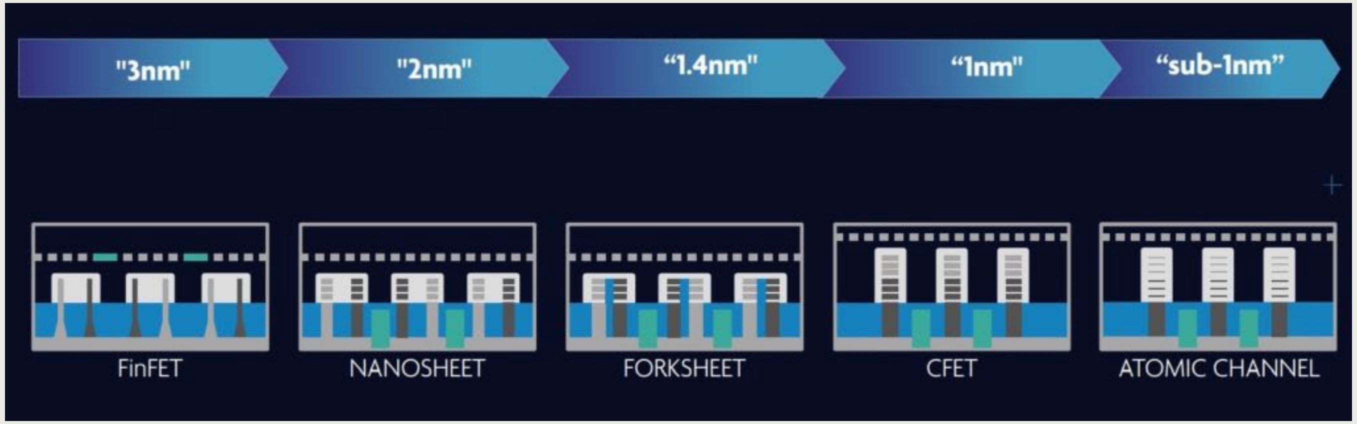
example 2: 3-D integration (source: CEA-Leti's 2015 roadmap)



Research context at quest

Moore, Moorer, Moorest.

example 3: imec's Transistor Technology Roadmap (Source: imec, 2022)



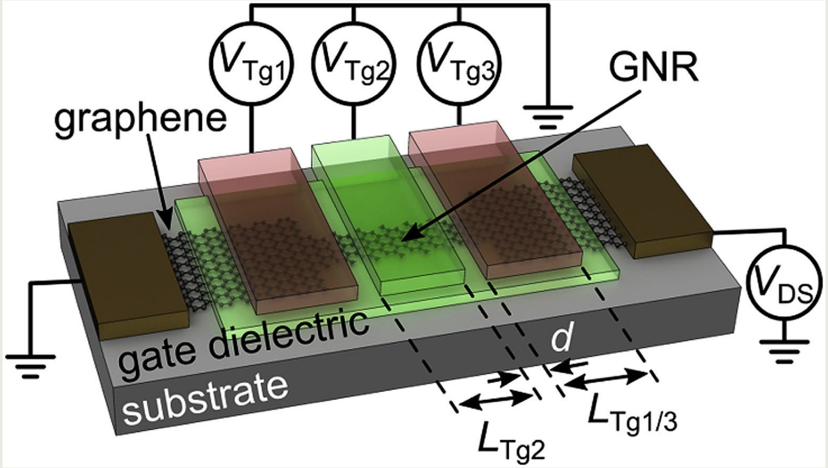
Physical phenomena

- Charge carrier confinement, ballistic transport
- Tunnel effect, Klein effect, …

Modeling challenges

- Quantum mechanical (QM) aspects
- *Ab Initio* (↔ macroscopic conductivity models)
- Multiphysics (QM/EM)

example 4: Sub-10 nm graphene nano-ribbon tunnel field-effect transistor



Research context at quest

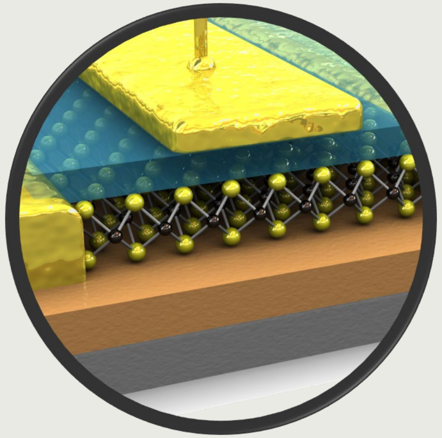
Why do we construct (multiscale and multiphysics) computational techniques?

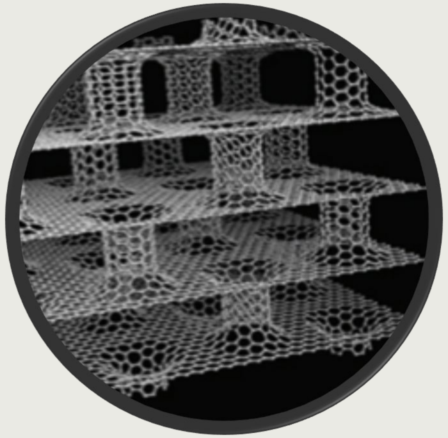
Electronic, nano- and quantum devices: heavily researched (applications / manufacturability)

Physical phenomena occurring in these devices are not always well -understood

Computational tools and models lead to

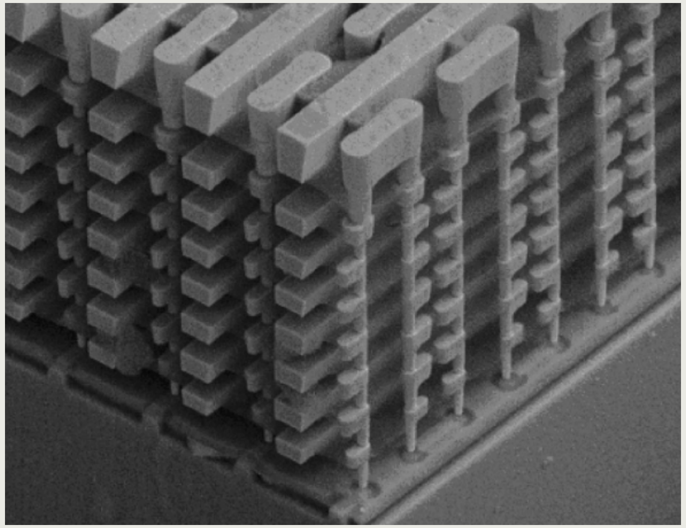
> a more thorough insight in the functioning of these novel devices and systems;
>
> computer aided design software, avoiding trial and error during development.





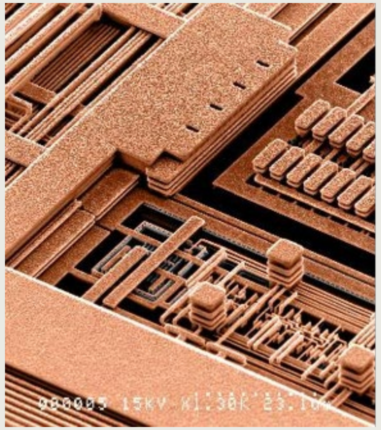
Research context at quest

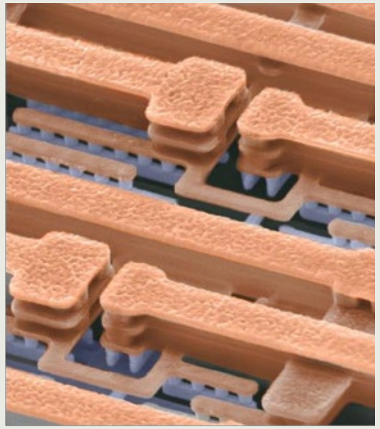
Modeling of interconnects structures (on -PCB and on -chip).



Wish list

- heterogenous (dielectric and magnetic) materials
- good conductors -> skin effect, proximity effect
- semiconductors -> slow-wave effect
- full-wave -> **accuracy and electromagnetic interference** (EMI)
- broadband -> **signal integrity analysis**
- efficient





imec NOKIA KEYSIGHT TECHNOLOGIES

Full-wave broadband characterisation

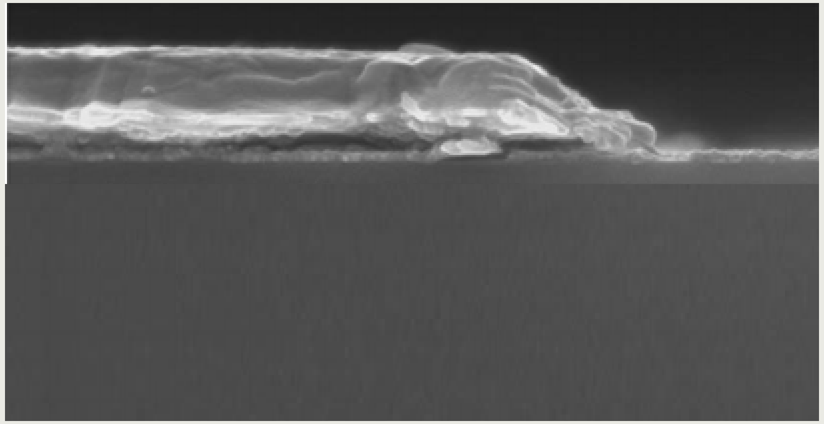
Modeling of interconnects structures (on -PCB and on-chip).

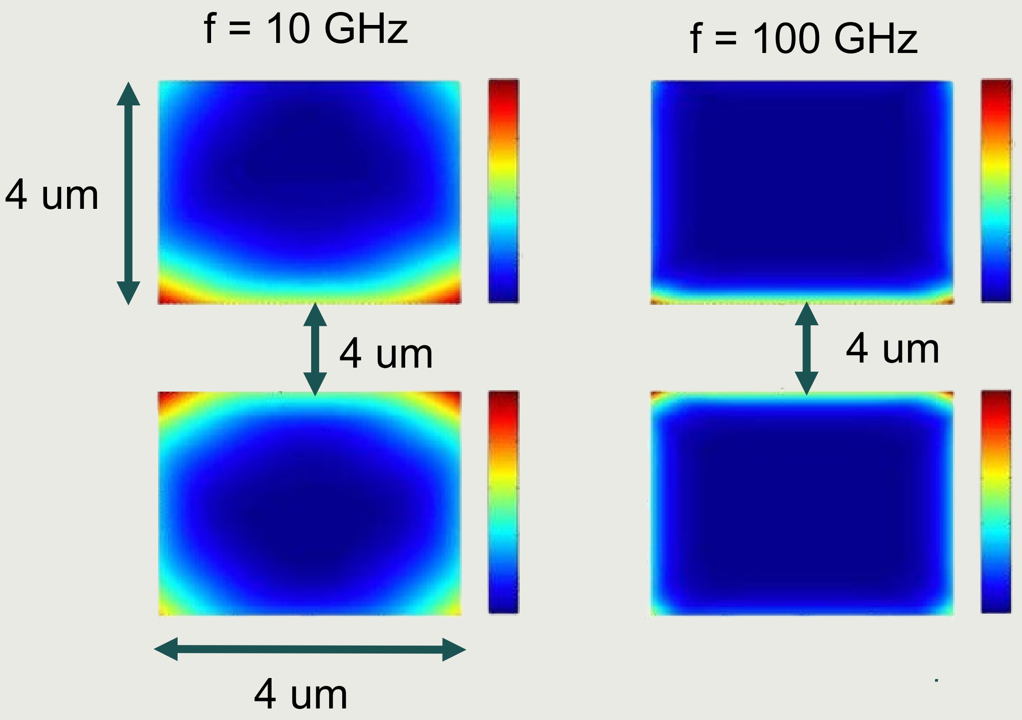
Miniaturization & increased operating frequency ask for **more accurate** and complete **modeling**

(Un)wanted **intricate** geometric **details** become increasingly impactful

Full wave solvers indispensable to capture effects such as the **skin effect** or the proximity effect

Challenging materials such as semiconductors or magnetic materials often **not accurately modeled** over large frequency ranges in (commercial) solvers





Computational electromagnetic techniques

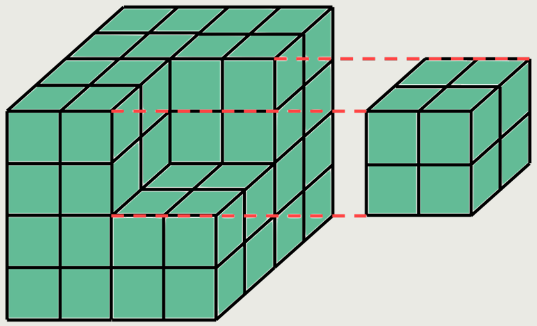
Boundary integral equations

Volumetric methods

Finite element method (FEM), finite-difference time-domain (FDTD),...

Large number of unknowns with sparse system matrix

Difficult to model EM phenomena such as skin effect, slow-wave effect,...

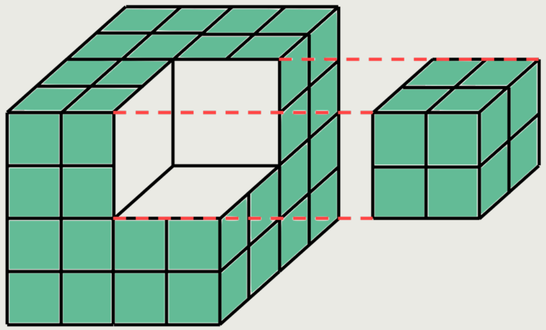


Boundary methods

Boundary element methods (BEM), boundary integral equations (BIE)

Smaller number of unknowns with dense system matrix

Difficulties with modeling vias, good conductors, skin effect, …

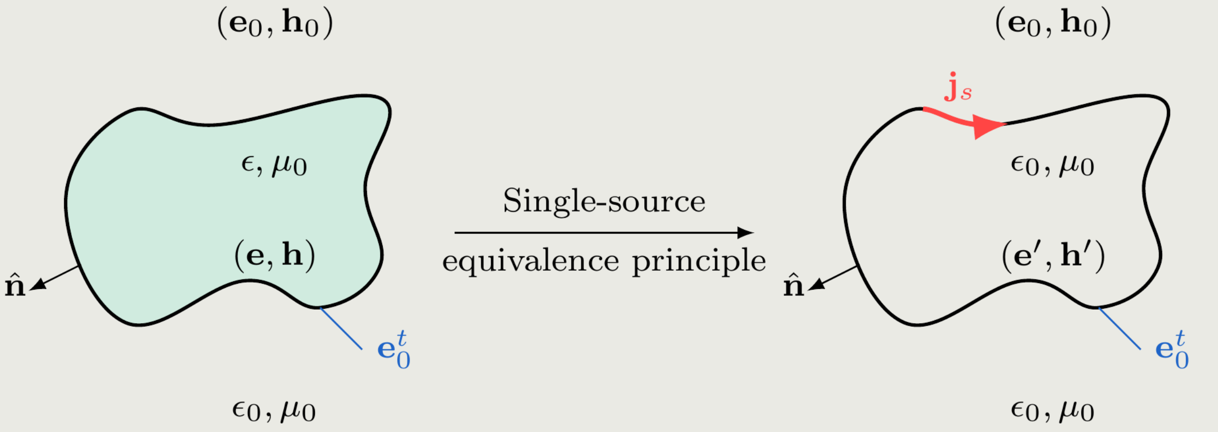


Differential surface admittance operator overcomes these difficulties!

Boundary integral equations

The Differential Surface Admittance operator

One way to find an expression for $\mathbf{j}_s$ is to introduce the Poincaré-Steklov operator in both situations



$$\hat{\mathbf{n}} \times \mathbf{h} = \mathcal{P} \circ \mathbf{e}^t \qquad \hat{\mathbf{n}} \times \mathbf{h}' = \mathcal{P}' \circ \mathbf{e}'^t$$

Imposing the boundary conditions, we then find an expression for the surface current density as

$$\mathbf{j}_s = (\mathcal{P} - \mathcal{P}') \circ \mathbf{e}_0^t = \mathcal{Y} \circ \mathbf{e}_0^t$$

Leading to the general definition of the **Differential Surface Admittance (DSA) operator,**

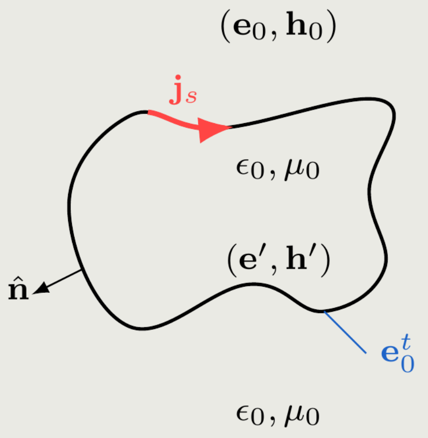
which can be integrated into a standard **Electric Field Integral Equation (EFIE)**

$$\hat{\mathbf{n}} \times \mathbf{e}_0^t(\mathbf{r}) = \hat{\mathbf{n}} \times \mathbf{e}_{\mathrm{inc}} - j\omega\mu_0 \hat{\mathbf{n}} \times \int_{\mathcal{S}} \overline{\overline{G}}_0(|\mathbf{r} - \mathbf{r}'|)\mathbf{j}_s(\mathbf{r}')\,\mathrm{d}\mathbf{r}'$$

Boundary integral equations

The Differential Surface Admittance operator

$$\mathbf{j}_s = (\mathcal{P} - \mathcal{P}') \circ \mathbf{e}_0^t = \mathcal{Y} \circ \mathbf{e}_0^t$$



How to construct $\mathcal{Y}$'

Through the traditional operators T and K

Most general formulation

Re-introduces Green's function in the (conductive) medium

Through the eigenmodes of the volume

Fully analytical -> fast and accurate

Quite restrictive in terms of geometry

Through the Fokas method

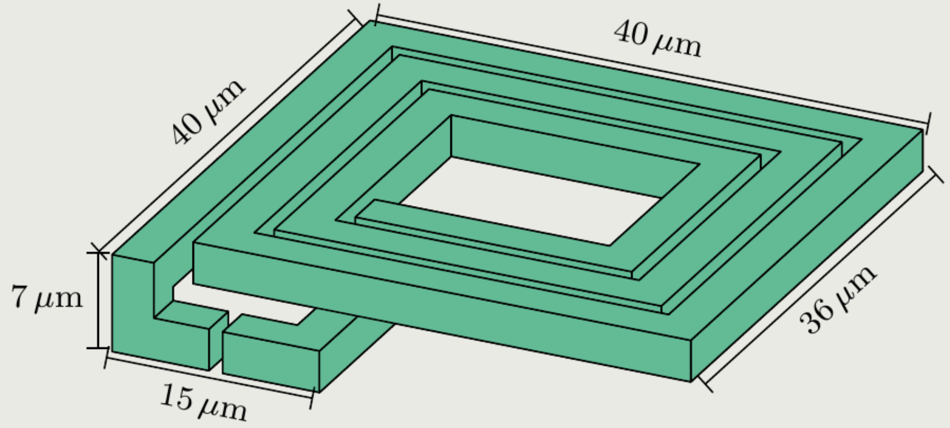
Allows for arbitrary polygons

Until recently only available in 2-D, now extended to 3-D

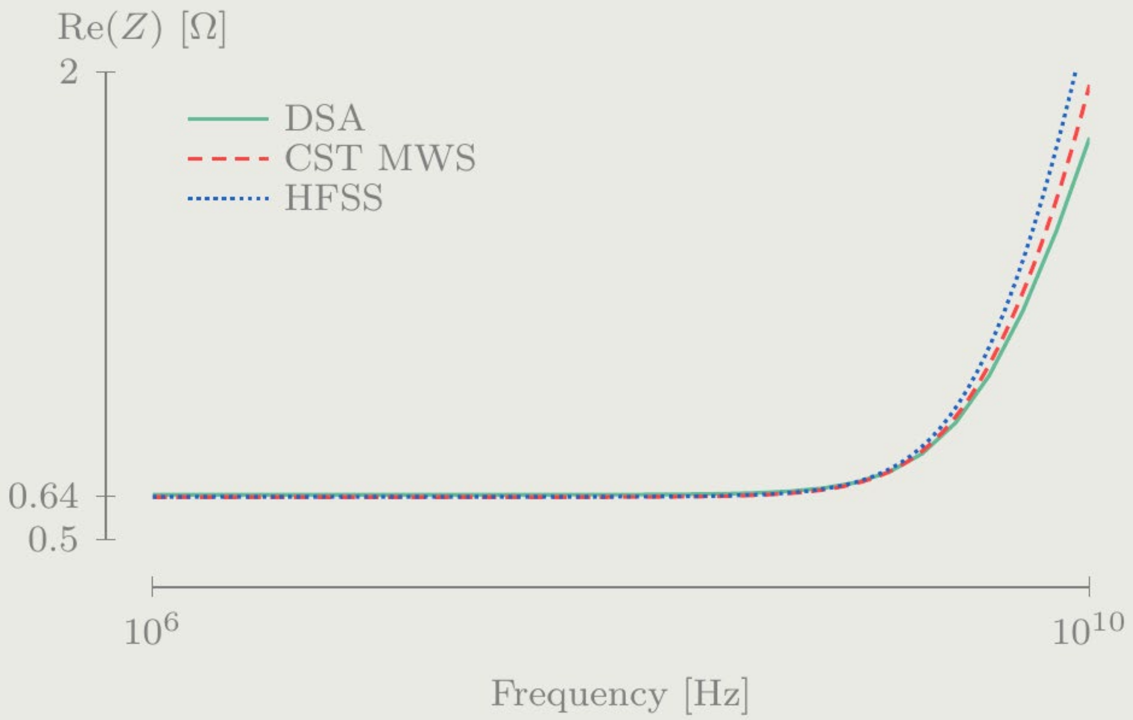
Skin effect in commercial solvers

Broadband simulation of a copper coil

Copper coil with 3x3 um cross -section



The expected $\sqrt{f}$ slope is not reproduced by the commercial solvers

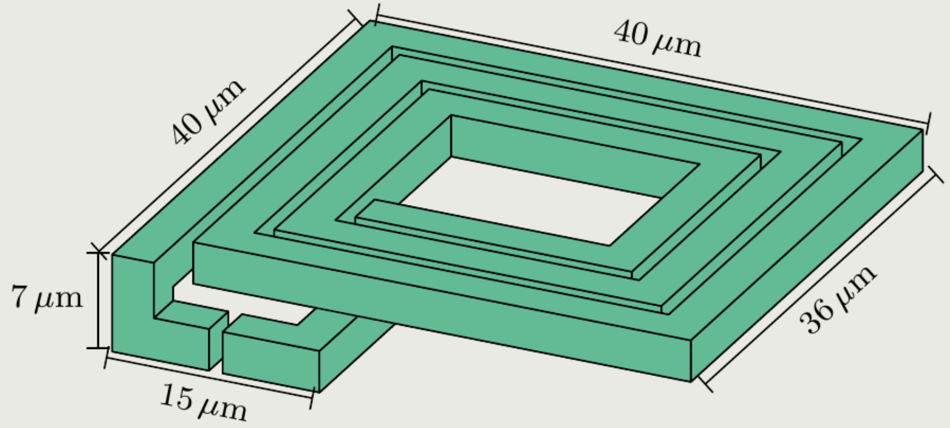


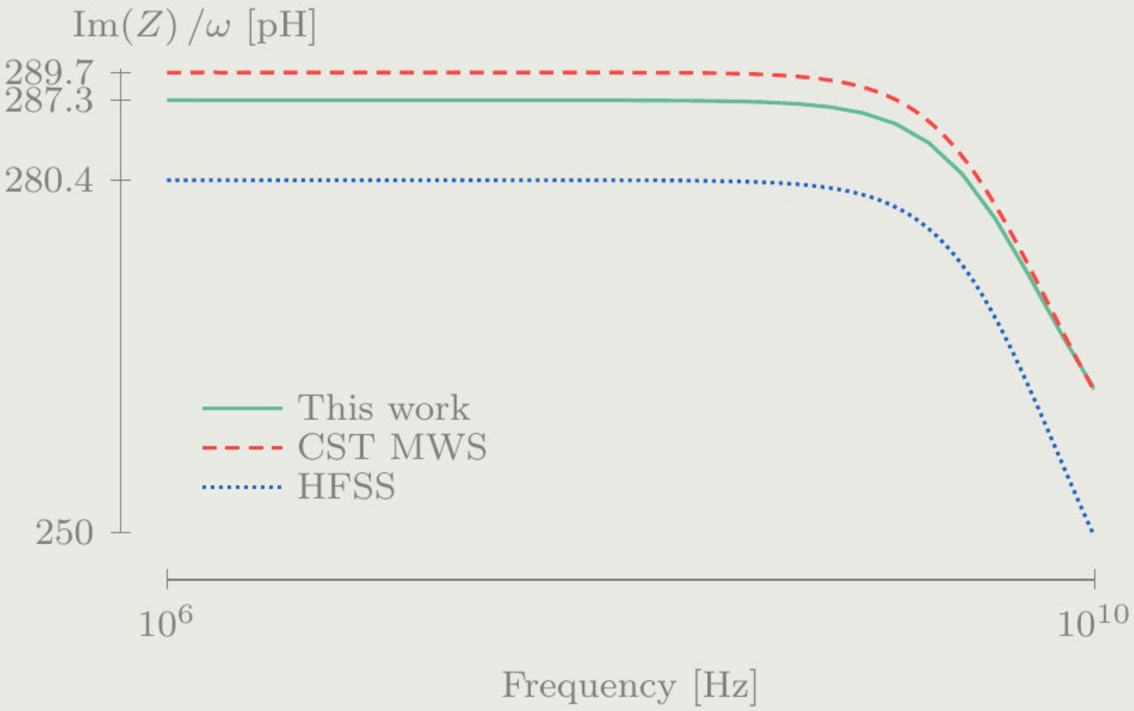
Skin effect in commercial solvers

Broadband simulation of a copper coil

Boundary box settings have a large impact on the inductance calculation

Downside of volumetric based methods



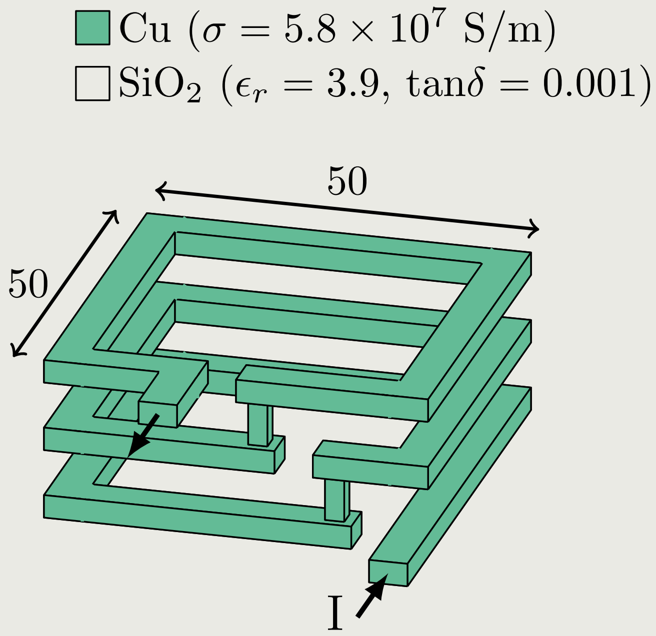


Skin effect in commercial solvers

Stacked spiral on -chip inductor

Key component for various applications in radio frequency and mixed -signal integrated circuits

Material choices reflect typical on -chip integration practices



Dimensions in um

Skin effect in commercial solvers

Stacked spiral on -chip inductor

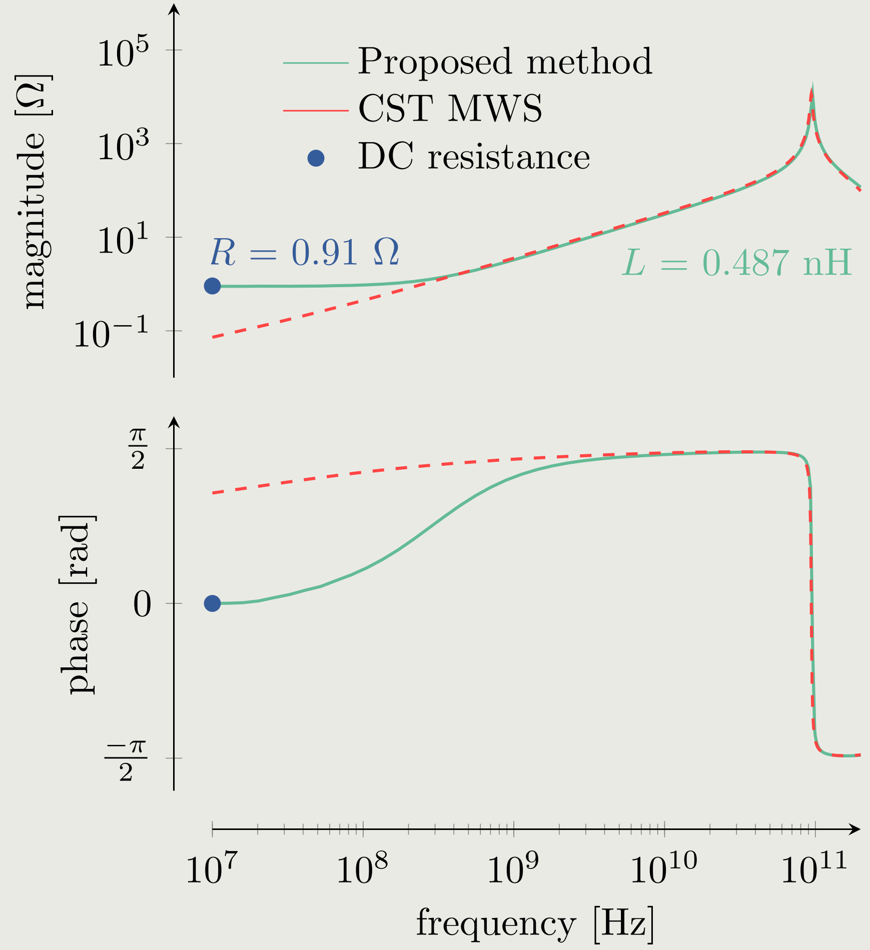
Validation with:

1. CST MWS
2. DC resistance (static solver)

Excellent agreement with CST MWS in inductive and self-resonant region

Converges to DC resistance at lower frequencies

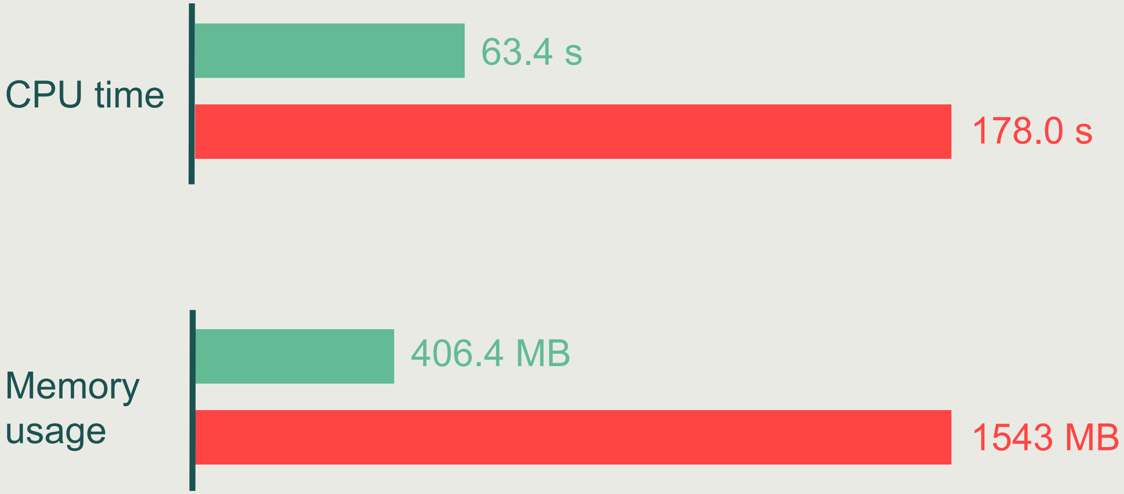
CST MWS was unable to accurately predict the DC resistance

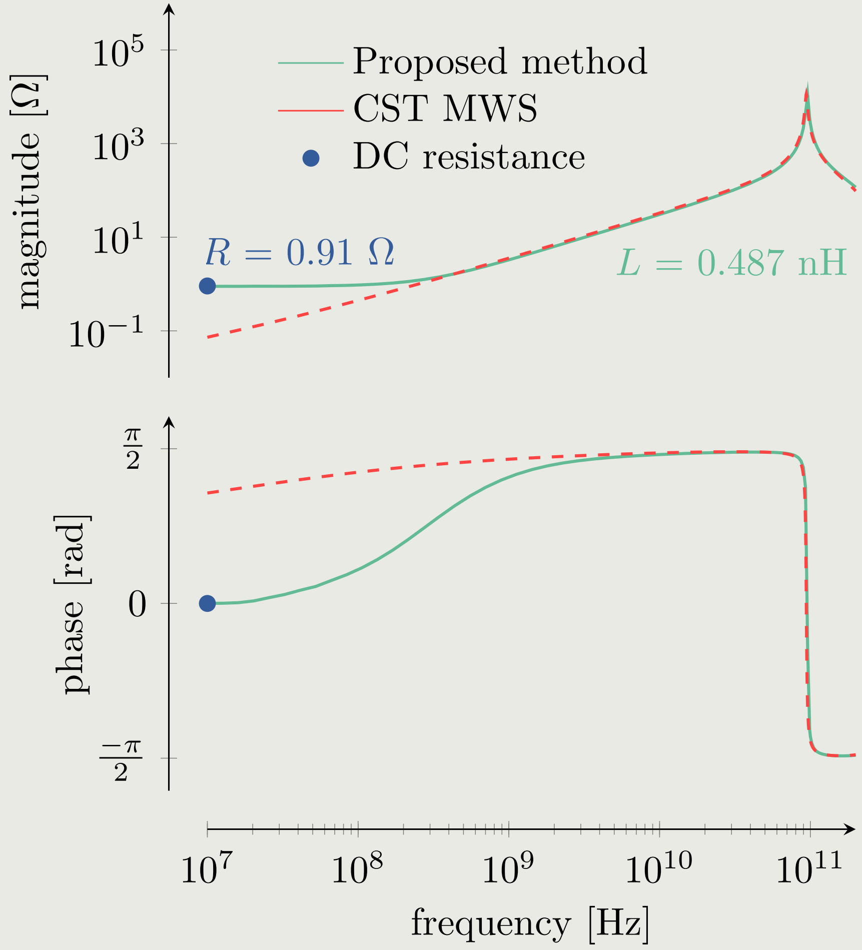


Skin effect in commercial solvers

Stacked spiral on -chip inductor

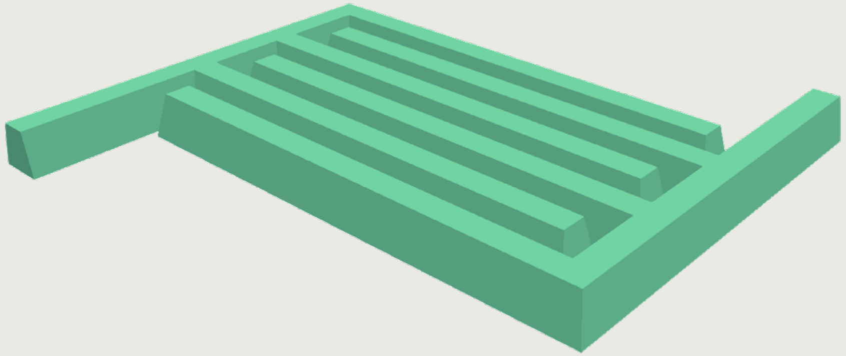
Significant improvement in computational efficiency (per frequency point)





Etching effects

Interdigital capacitor for on-chip applications

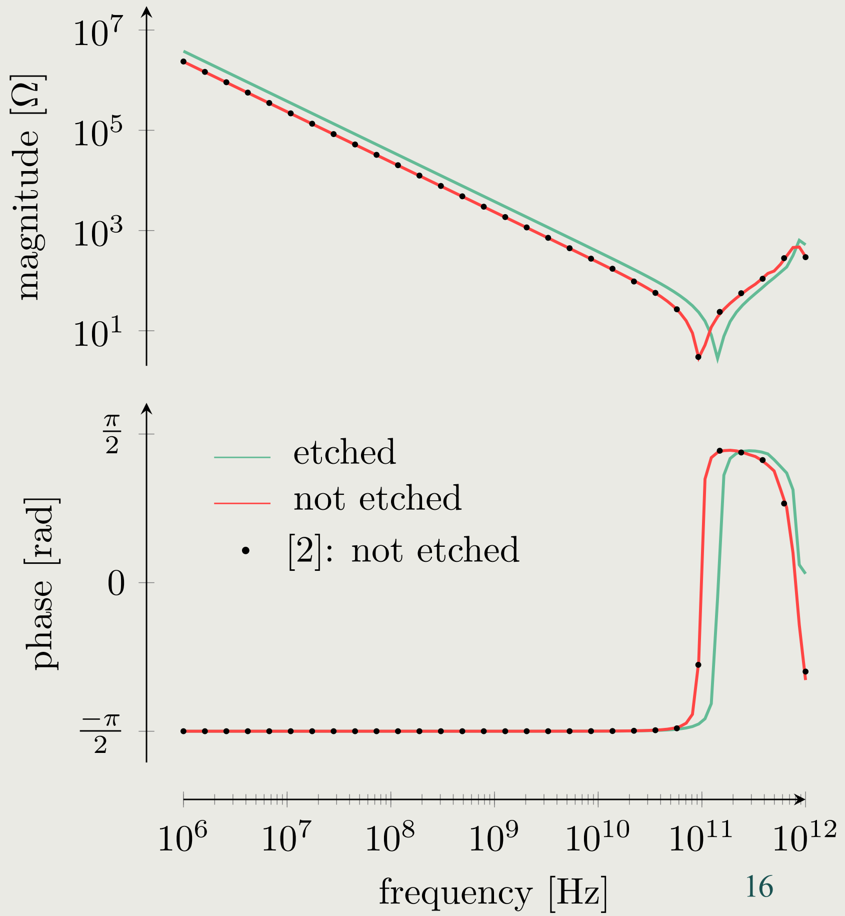


50 um by 50 um capacitor with 1 um gap between the digits

Square cross-section vs. etching angle of 78°

Etching reduces capacitance by 38.3 %

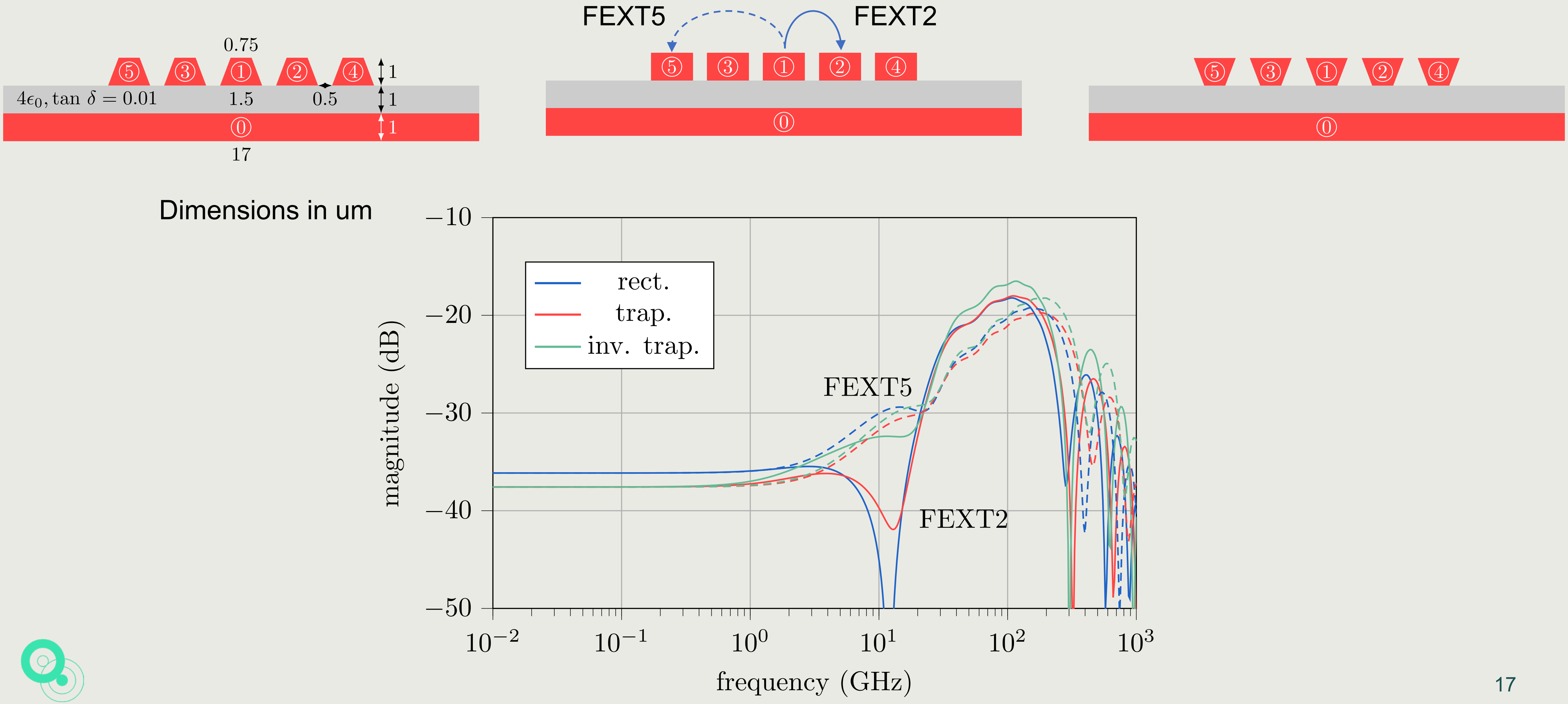
High-frequency behavior, i.e., self-resonance, is also impacted



[2] M. Huynen et al., IEEE T-MTT, 2020

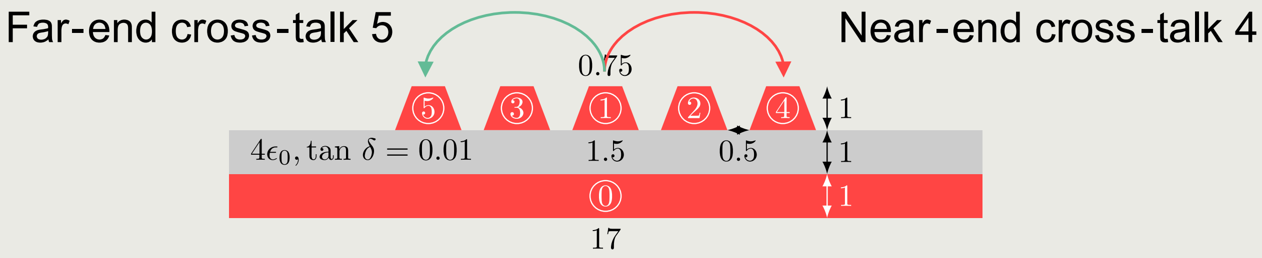
Etching effects

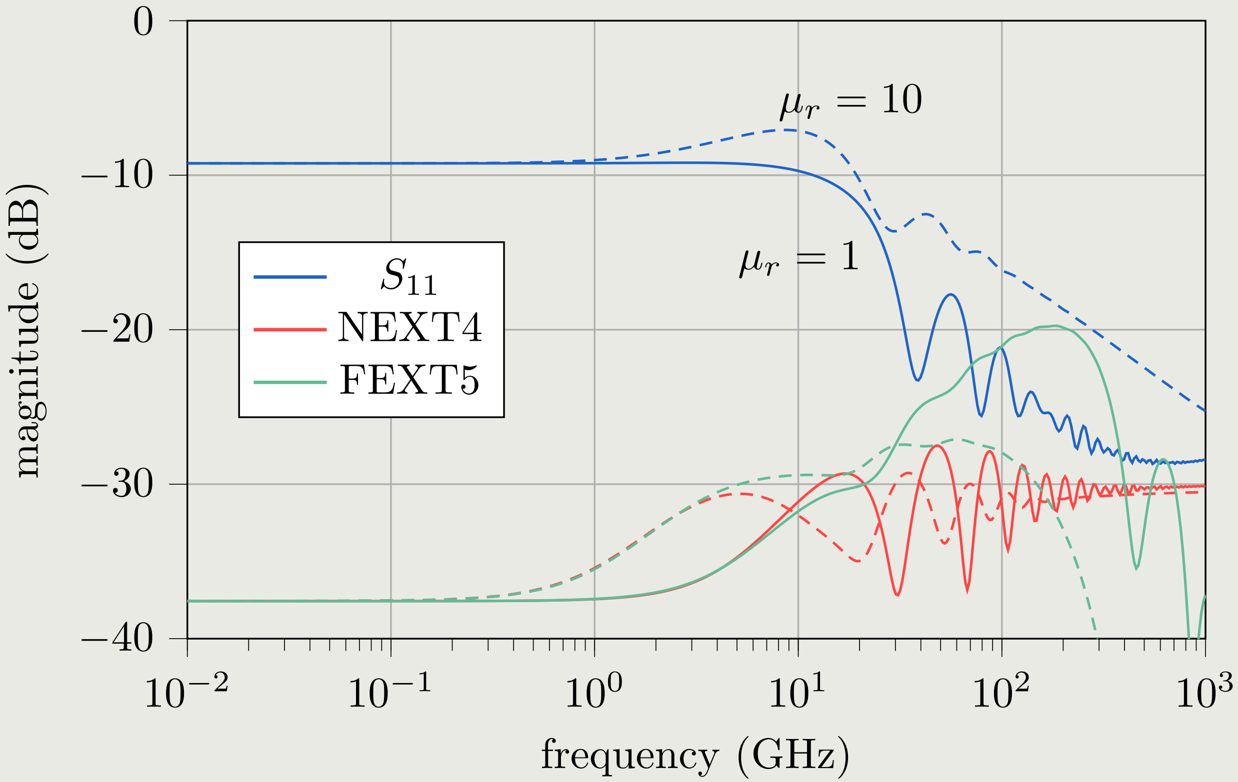
Far-end cross-talk (FEXT) in multiconductor TL strongly depends on conductor's shape



Magnetic materials

Magnetic materials heavily impact the signal integrity performance

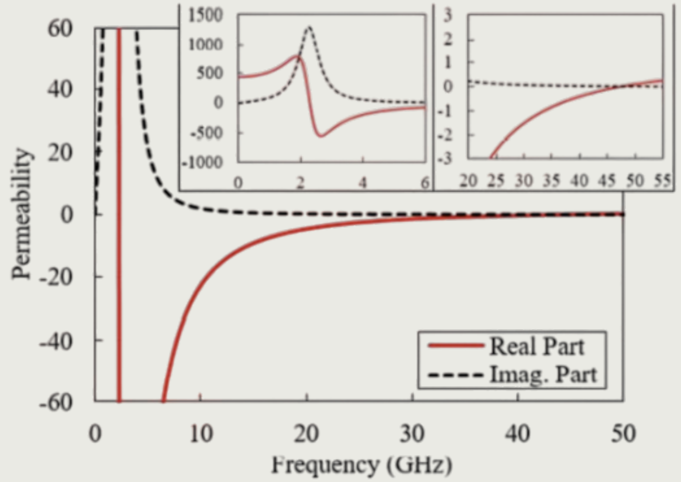




Magnetic materials

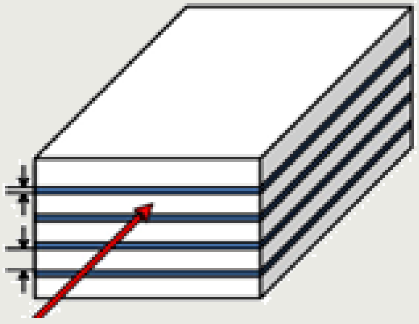
Alternating magnetic and non-magnetic conductors can reduce the skin effect

Materials such as cobalt exhibit a **negative permeability** in certain frequency ranges



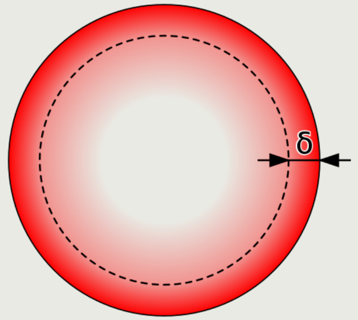
Alternating layers of non-magnetic conductors and magnetic material will exhibit a **lower average** $\mu_r < 1$ or even $\mu_r = 0$

$$\mu_{r,\mathrm{av}} = \frac{1 \cdot t_{\mathrm{cu}} + \mu_{r,\mathrm{mag}} \cdot t_{\mathrm{mag}}}{t_{\mathrm{cu}} + t_{\mathrm{mag}}}$$



This **reduces the skin effect** and hence losses in interconnects

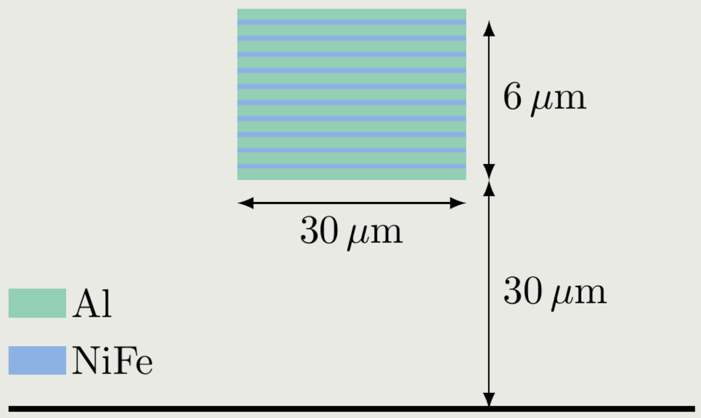
$$\delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}}$$

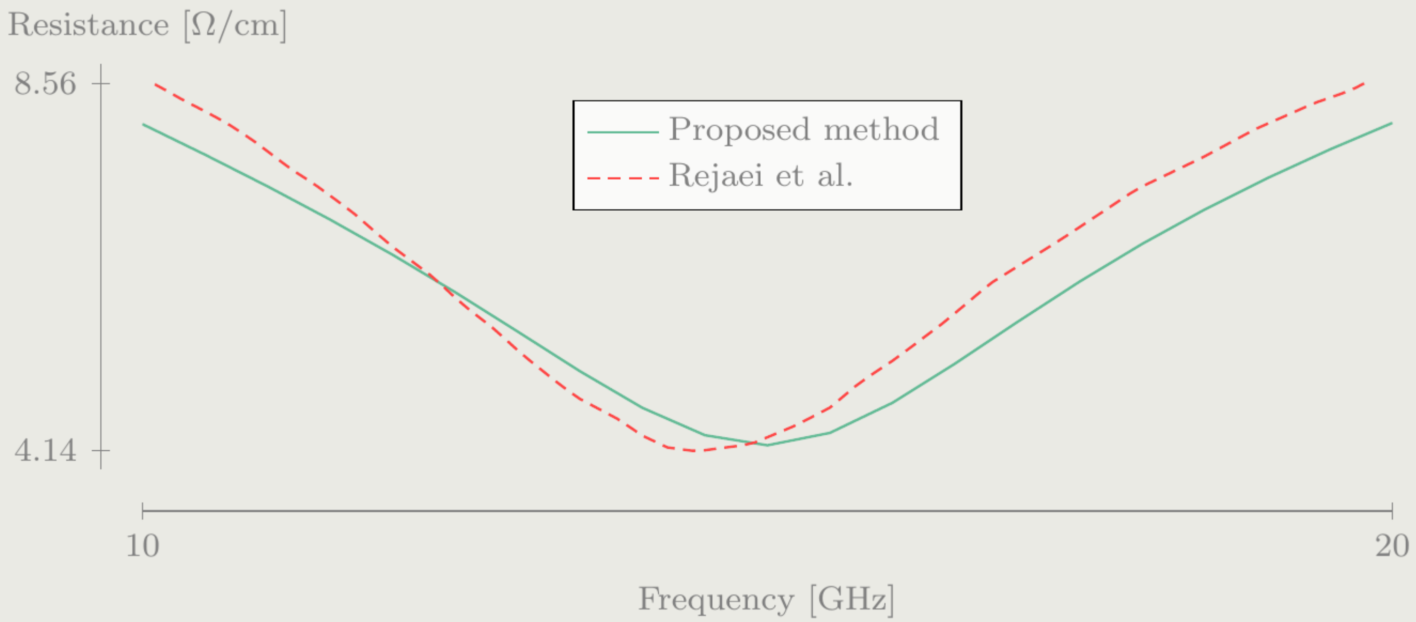


Magnetic materials

The reduced skin effect reduces the resistance of the combined stack

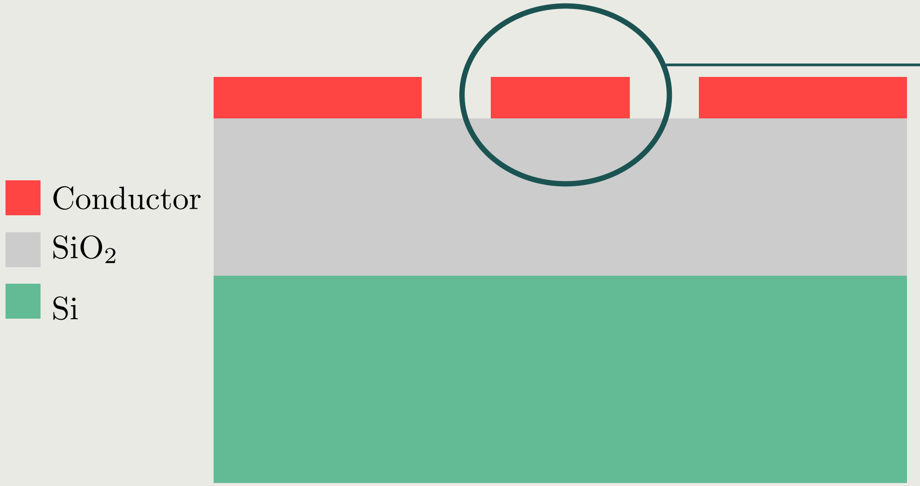
Microstrip line with metaconductor stack of aluminium and nickel-iron

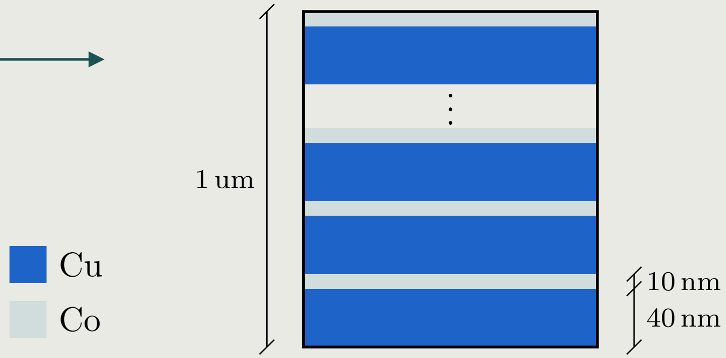


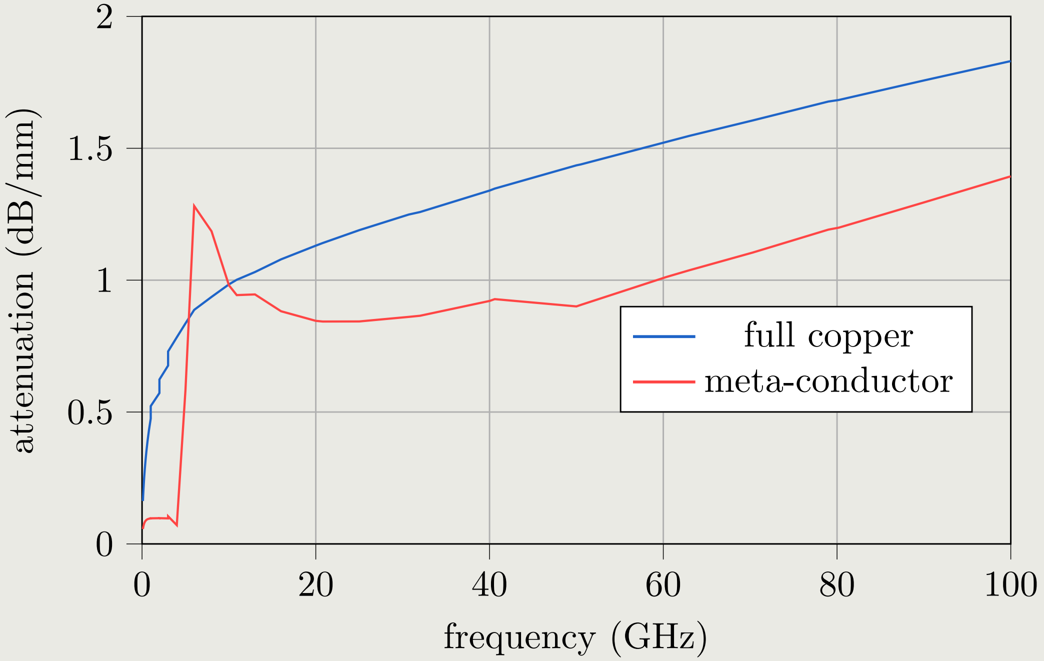


Magnetic materials

The reduced skin effect significantly lowers the attenuation over a large frequency range







Conclusions

The inclusion of good but **lossy conductors** is a **challenge** for computational methods, including boundary integral equation formulations

Various **approaches** exist of which the **differential surface admittance operator** presents an interesting **alternative** with its own benefits

The DSA formulations exhibit a very **accurate broadband** capturing of a developing **skin-effect**, enabling high-quality **signal integrity analysis**

Additionally, it provides a **flexible alternative** with strong performance for innovative, emerging **interconnect topologies** and **passive components** quest.

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GHENT UNIVERSITY

imec

Technologiepark – Zwijnaarde 126, B-9052 Gent, Belgium
T +32 9 xxx xx xx — email@ugent.be
www.QuestLab.be

Name SURNAME, Job Title.