Small- and large-signal modeling of silicon-based substrates

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Content

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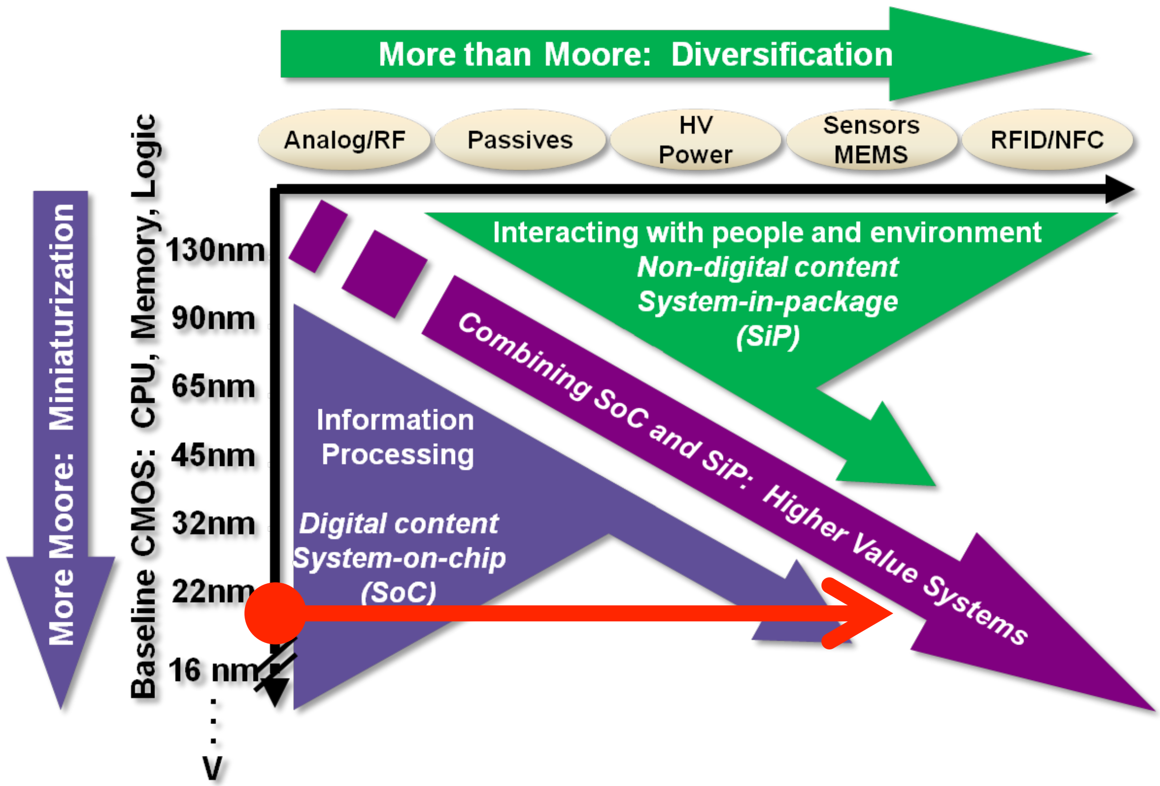
  - Substrate impact
  - Modeling tools + examples of use
- Large-signal modeling
  - Motivation
  - Non-linear signal distortion
  - Modeling approach
  - Carrier dynamics and finite inertia
  - Dips and saturations in HD components
- Conclusions

Context


More than Moore: Diversification
Analog/RF
Passives
HV Power
Sensors MEMS
RFID/NFC
More Moore: Miniaturization
Baseline CMOS: CPU, Memory, Logic
130nm
90nm
65nm
45nm
32nm
22nm
16 nm
V
Interacting with people and environment
Non-digital content
System-in-package
(SiP)
Combining SoC and SiP: Higher Value Systems
Information Processing
Digital content
System-on-chip
(SoC)

Context

Digital chip + RF chip(s) = More process **COST!**

=

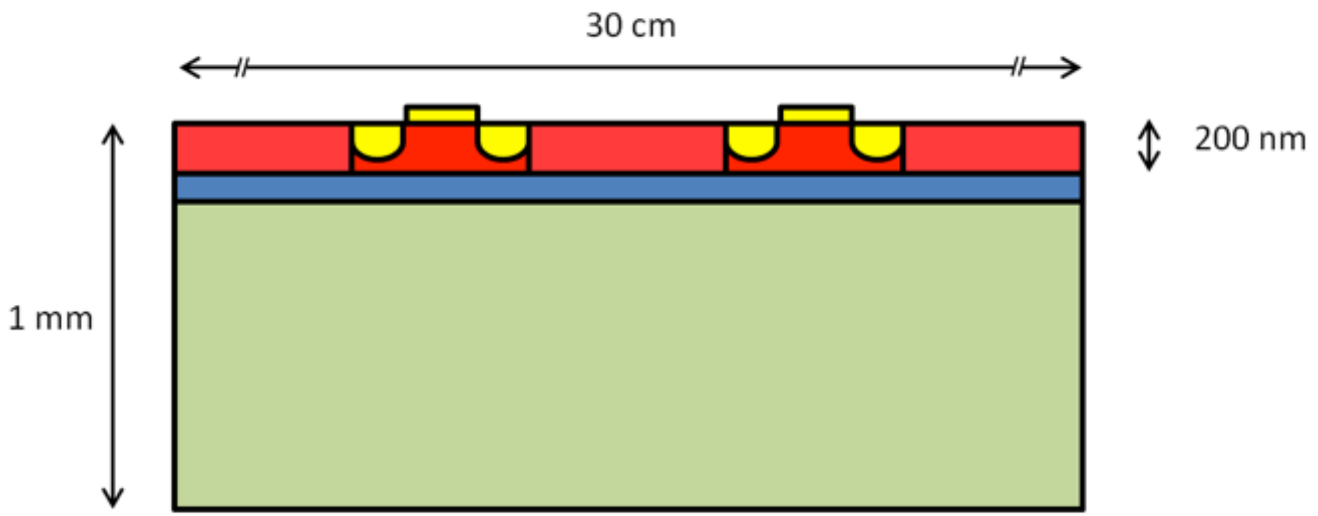
⇒ Integrate on a single substrate:

Cost ↘

Performance ↗

Context

- **What is a substrate??**
- For a long time considered solely as a **mechanical support**.

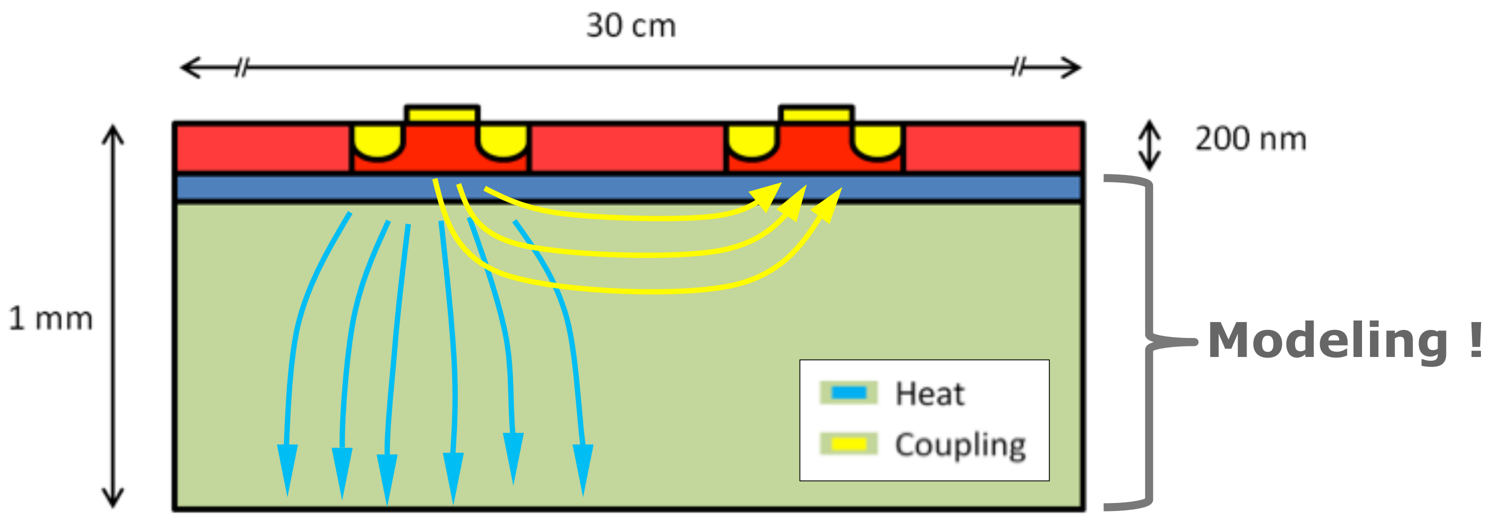


Context

What is a substrate??

Now however this mechanical support must provide:

- Thermal evacuation
- Low loss
- Low coupling
- Linearity

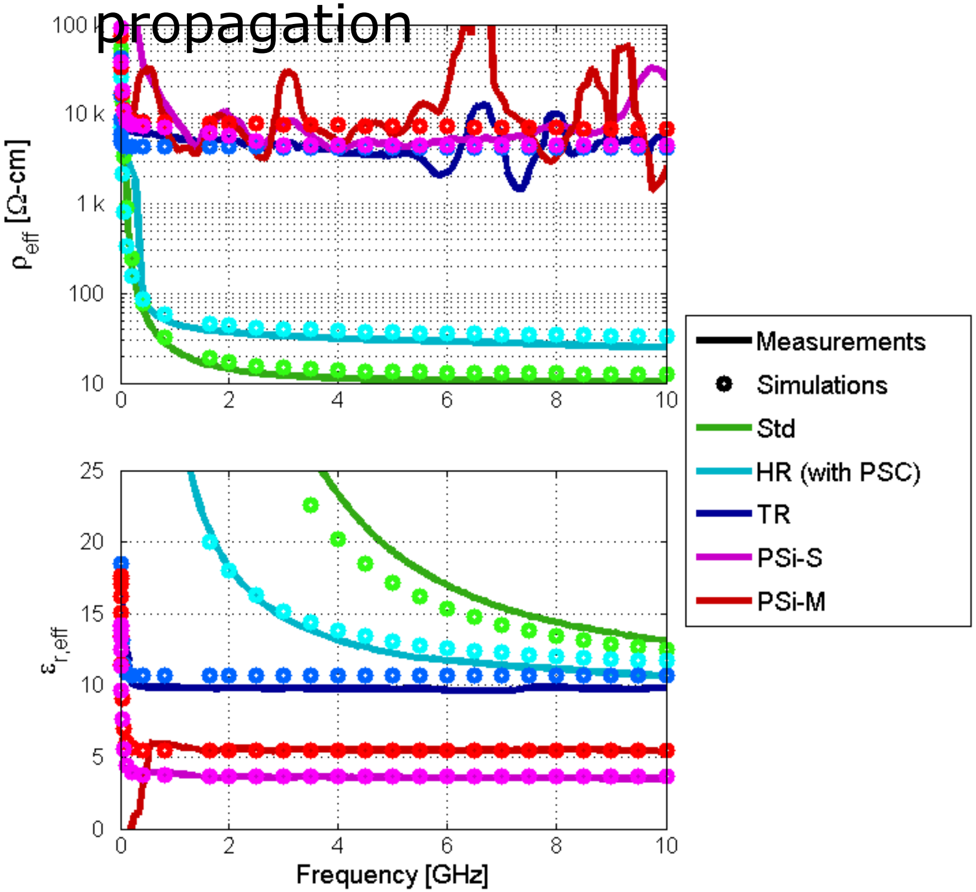


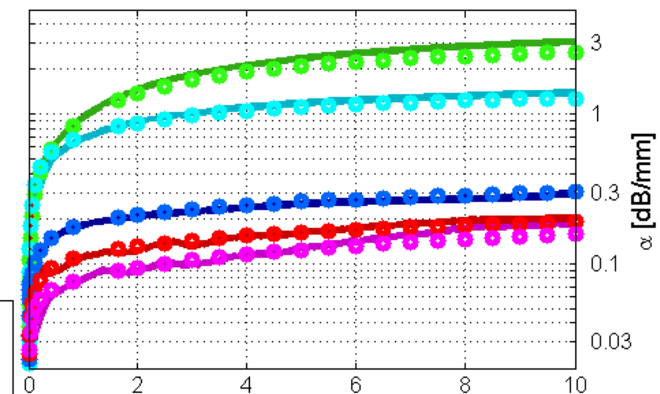
Modeling tools

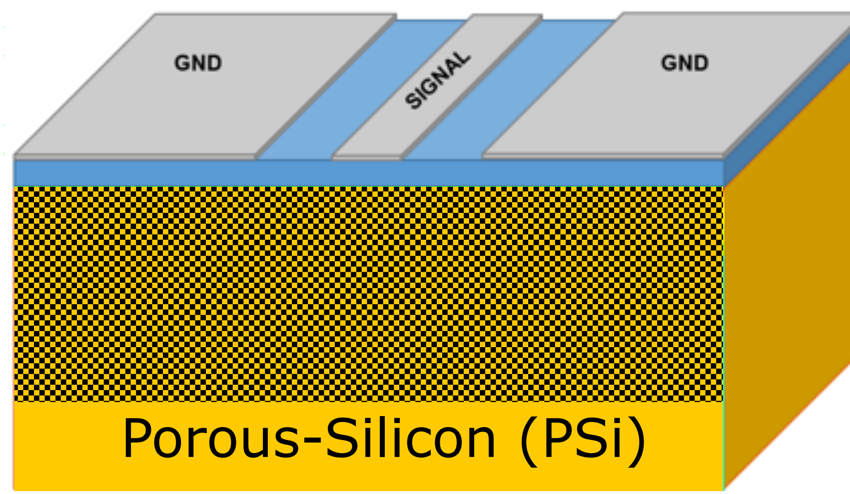
Method	Equations	Speed	Comment	Usability
FEM Device physics (Silvaco, Synopsys,…)	**Transport equations** (semiconductor)	Very slow	**Non-linear** capabilities **Not propagation**	
FEM Full-wave (HFSS,…)	**Maxwell**	slow	**Purely linear** **Propagation** Substrate inhomogeneity difficult to incorporate	
MOM (BEM) (ADS momentum, …)		Fast		PDK ready
FDM	Kirchhoff	Very fast	Discrete lumped **Not propagation**	PDK ready
Hybrid			**Purely linear** MOM+MOM MOM+FEM	PDK ready

Substrate impact: **CPW lines**

Small-signal modeling : FEM transport equations + closed form expressions of CPW propagation

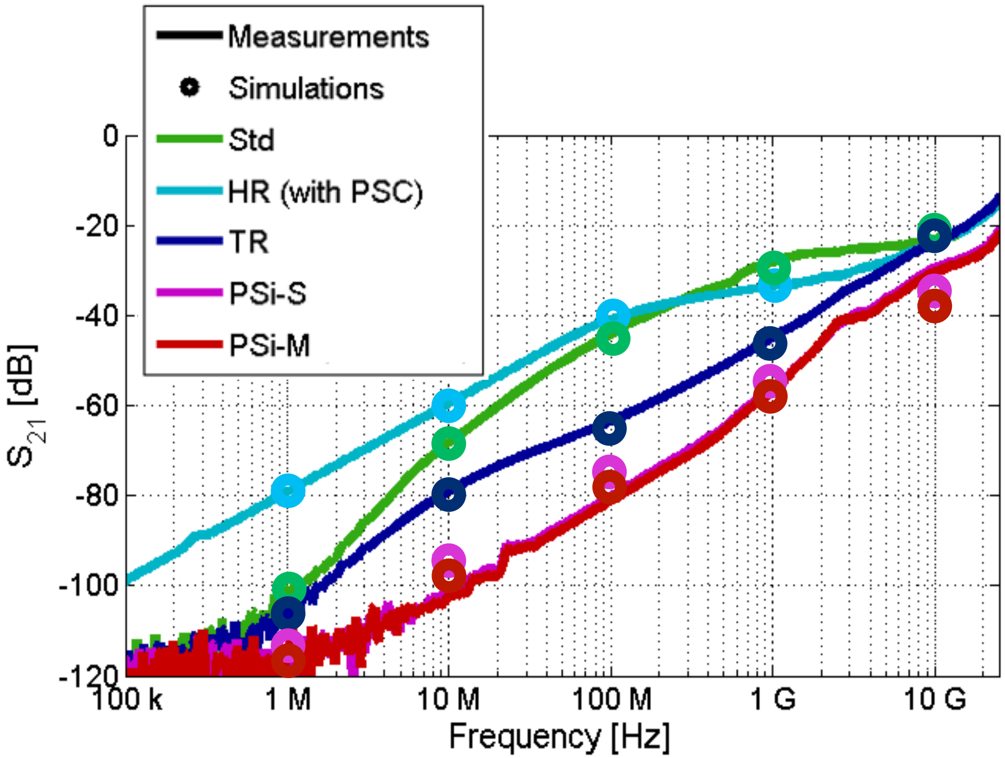


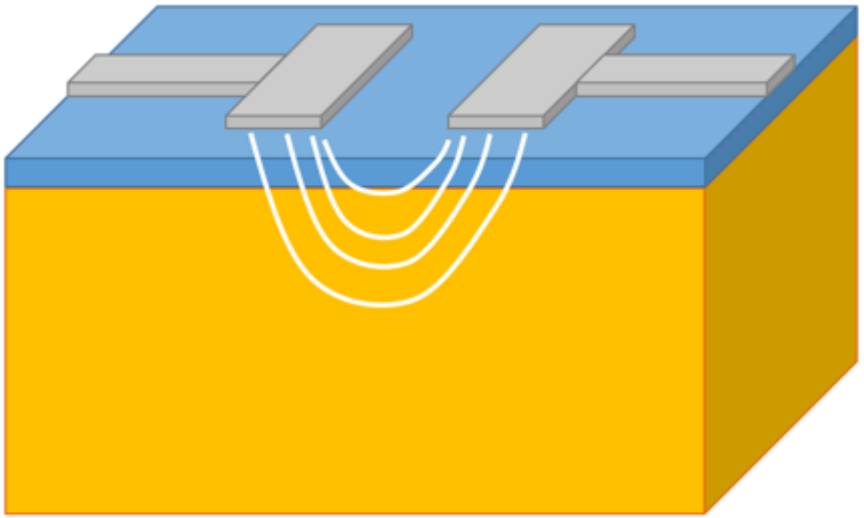




Substrate impact: Crosstalk

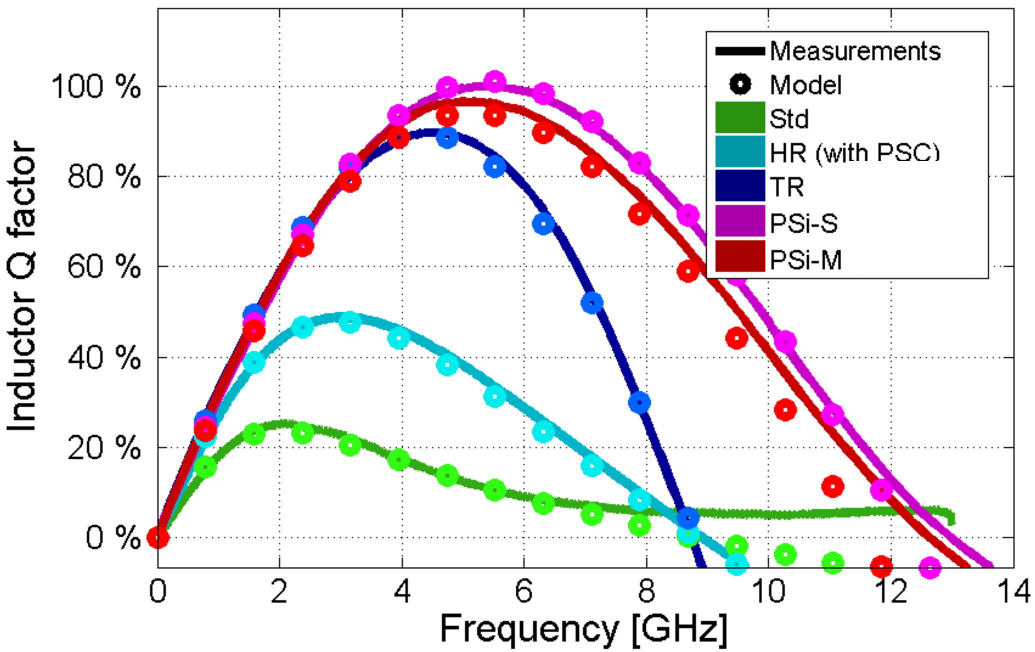
Small-signal modeling : FEM transport equations

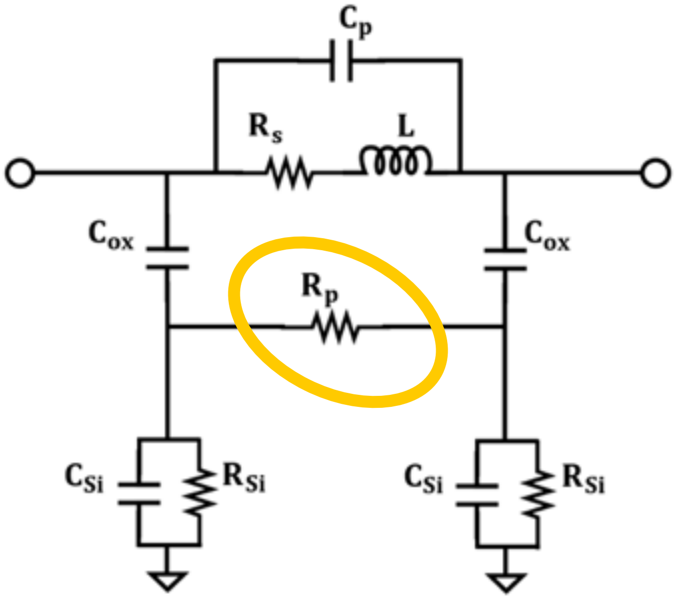




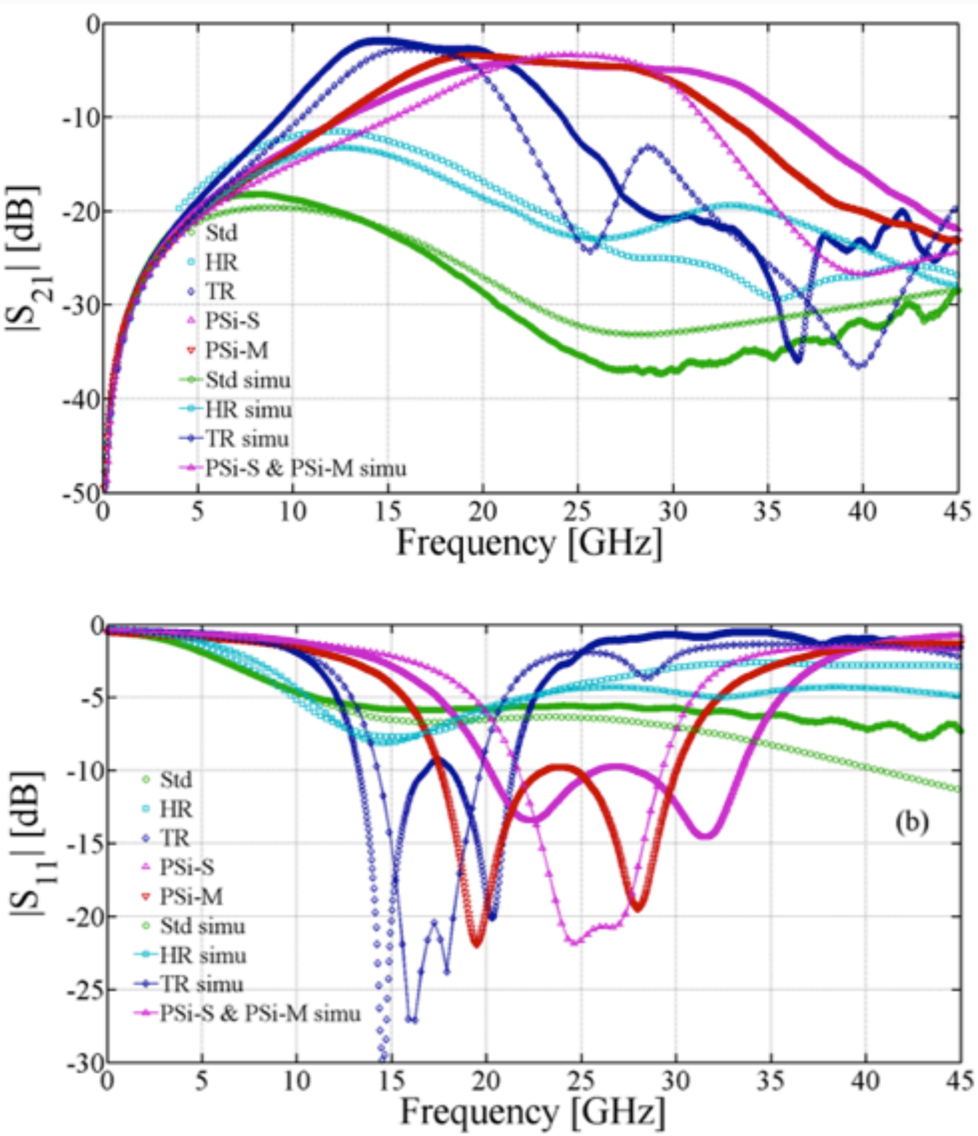
Substrate impact: **Inductor quality**

Small-signal modeling : MOM modeling (inhomogeneous substr-ate profile from FEM transport equations)





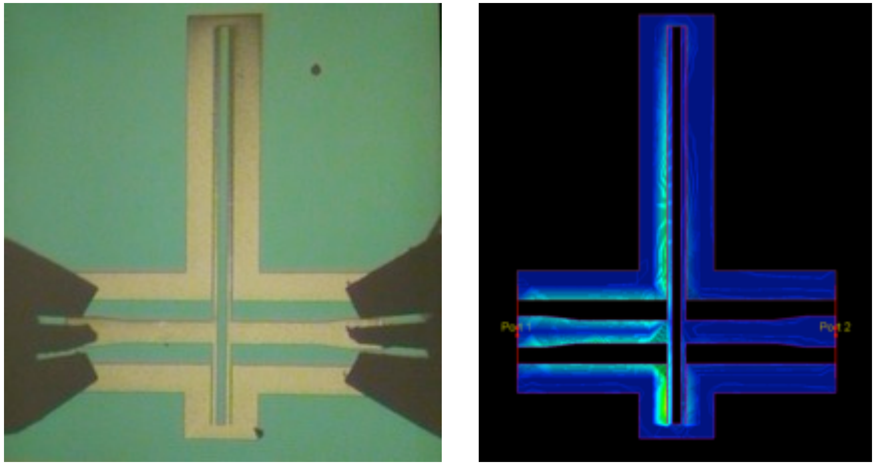
Substrate impact: **Bandpass filter**



Small-signal modeling:

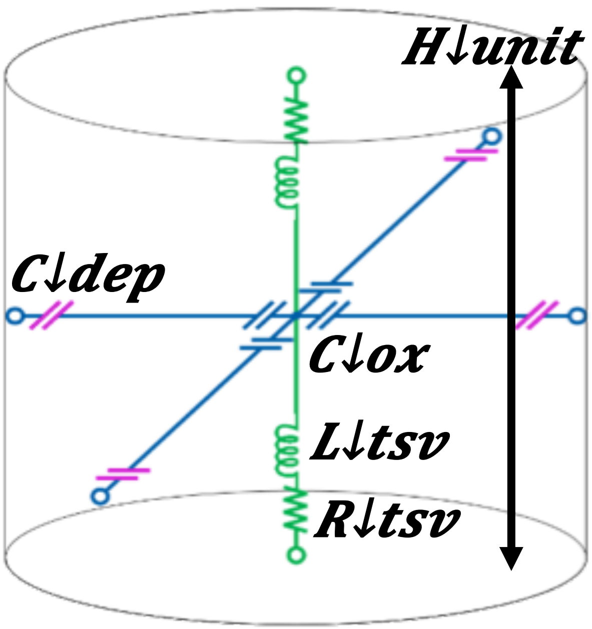
MOM modeling (inhomogeneous substrate profile from FEM transport equations)

Measurements **MOM**

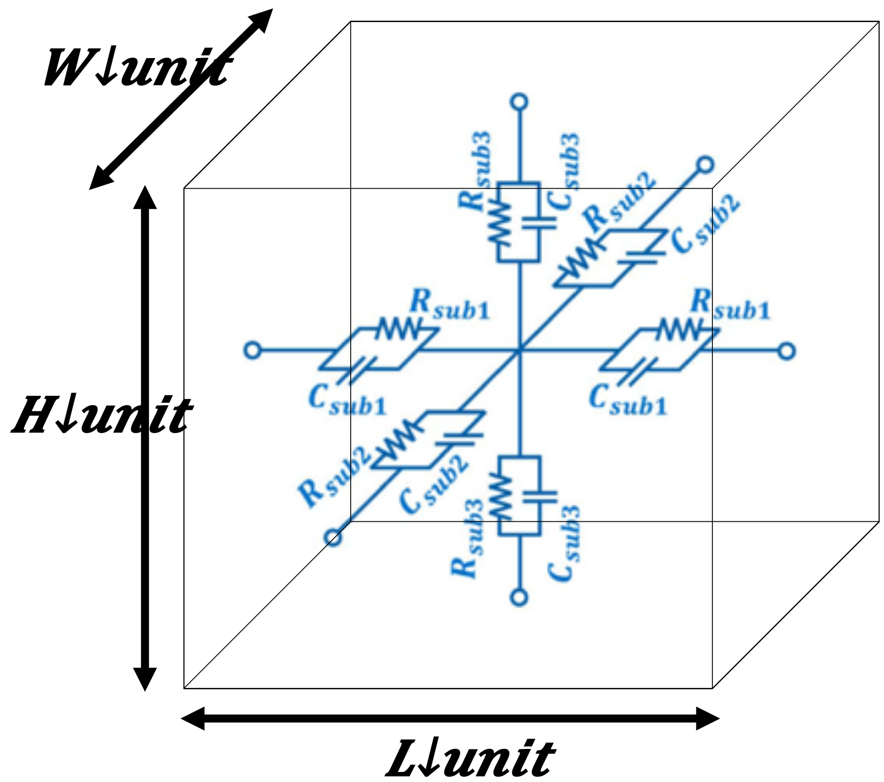


FDM modeling example: Coupling in 3DICs

TSV unit cell

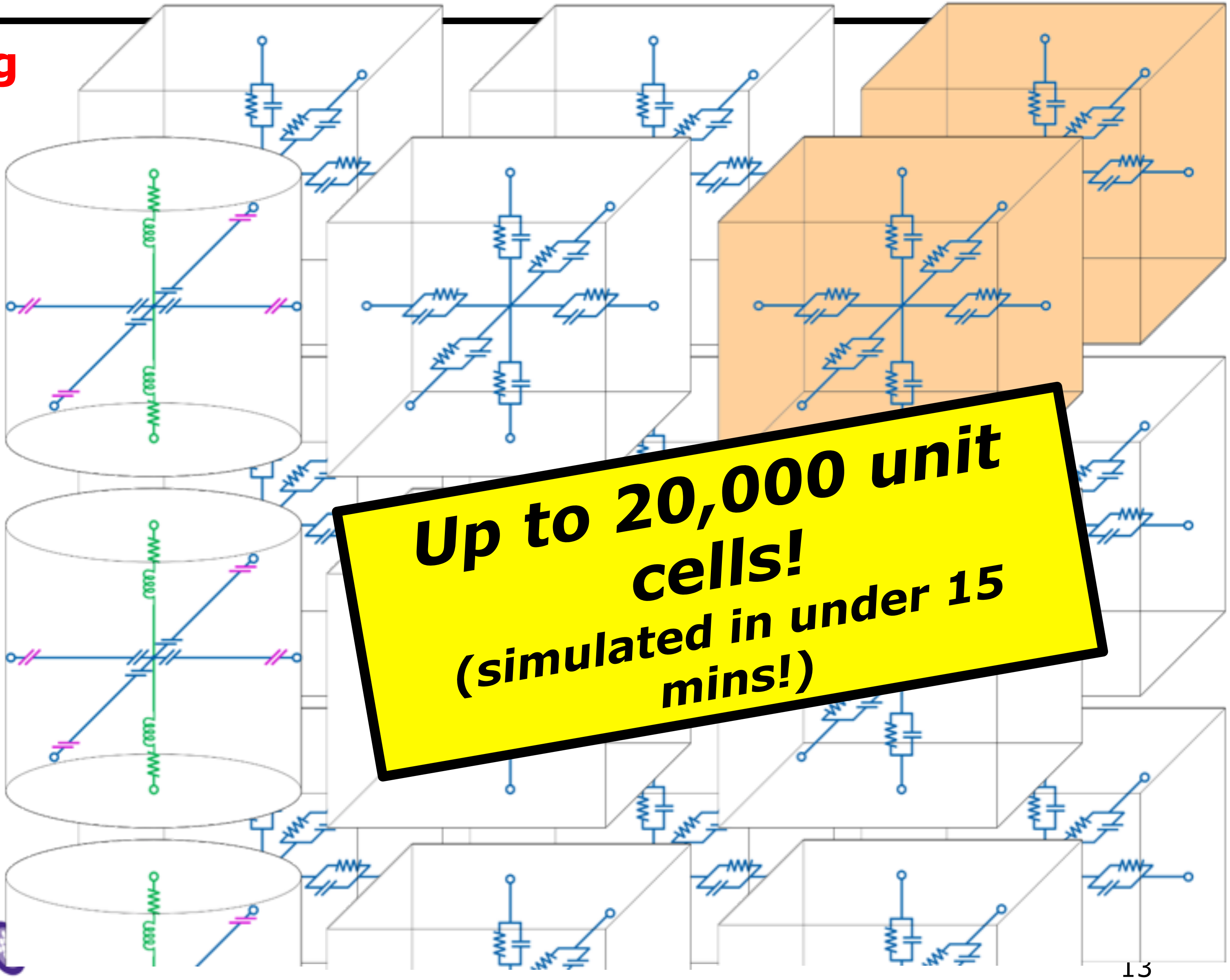


Substrate unit cell



FDM modeling example: **Coupling in 3DICs**

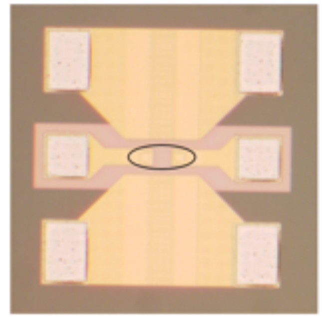
Connecting the cells:

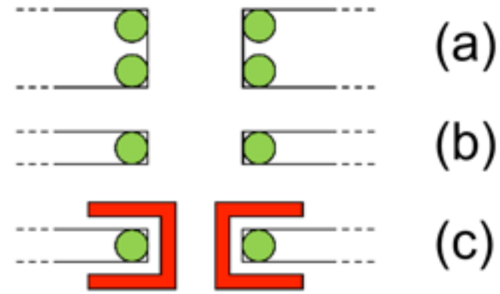


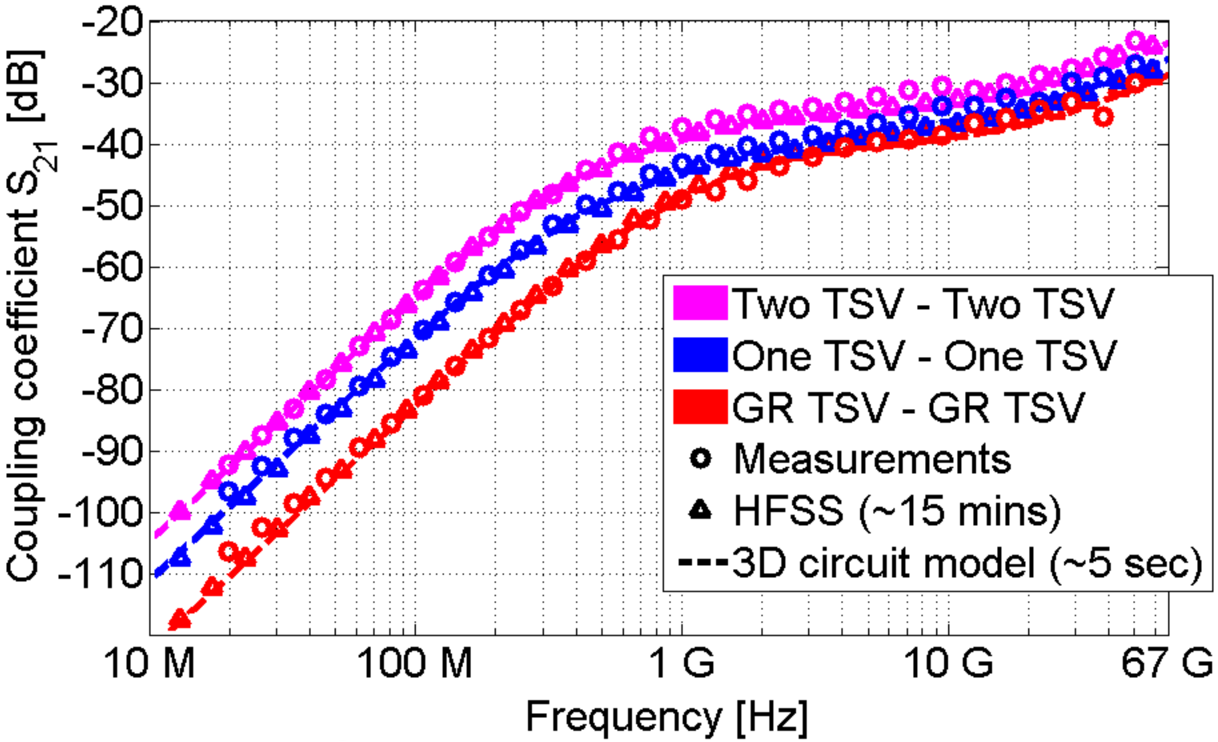
FDM modeling example: **Coupling in 3DICs**

Three coupling test structures are considered to validate the model

(a) Two TSV to Two TSV
(b) One TSV to One TSV
(c) GR TSV to GR TSV

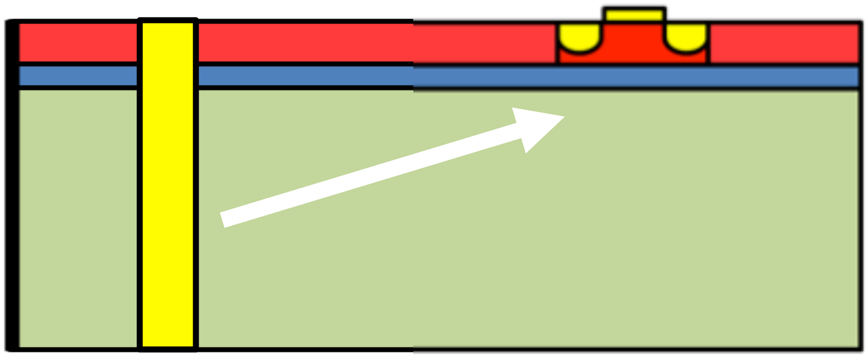


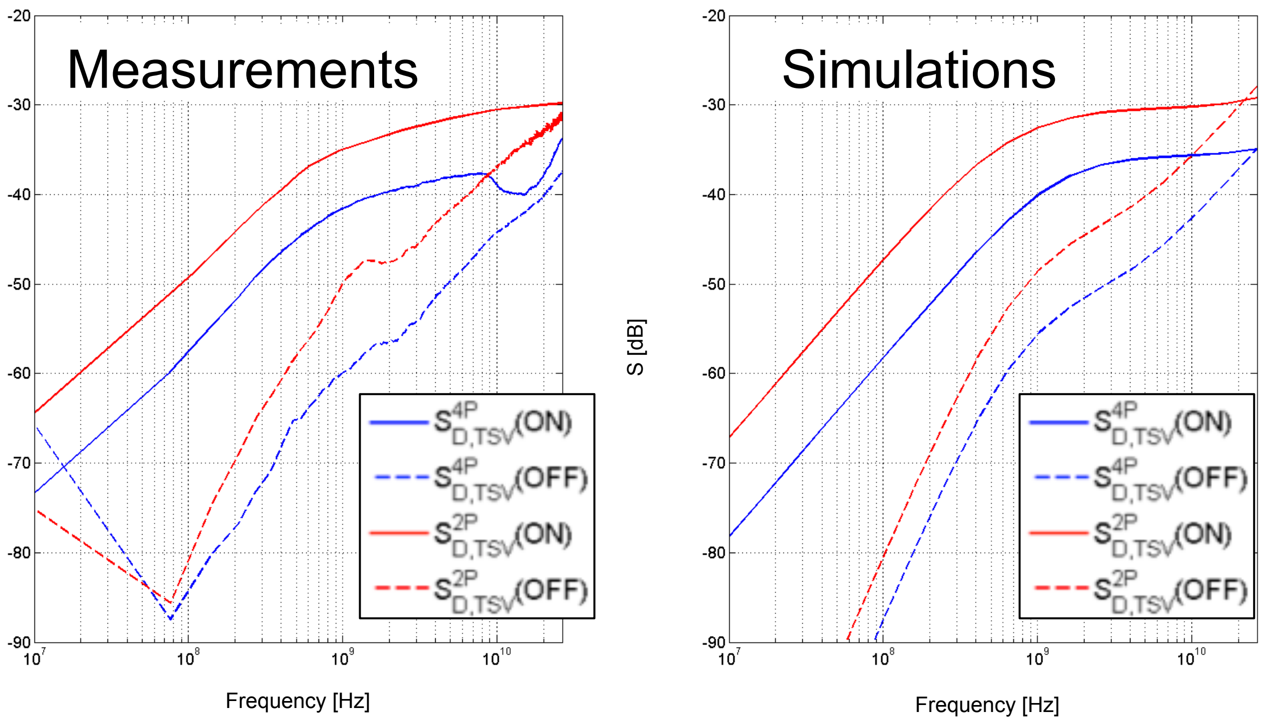




- Agreement to both HFSS and RF measurements
- Complex field distributions are accurately modeled
- Much faster than HFSS: Maxwell → Kirchhoff
  - ⇒ Opens the door to larger, more complex simulations

FDM modeling example: **Coupling in 3DICs**





Non-linear substrate modeling

Motivation

Non-linearities distort signal

⇒ **Information quality degraded**

Origins?

Active devices

Passive devices ⇒ from substrate!

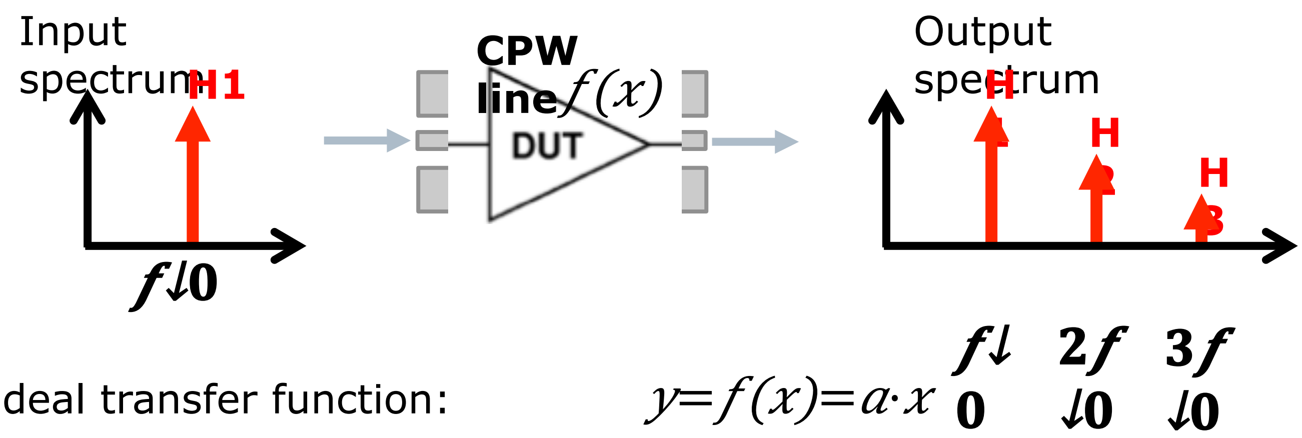
***Example*:**

SOI RF switches

Non-linearity of interconnects dominate those of switch!

⇒ from substrate!

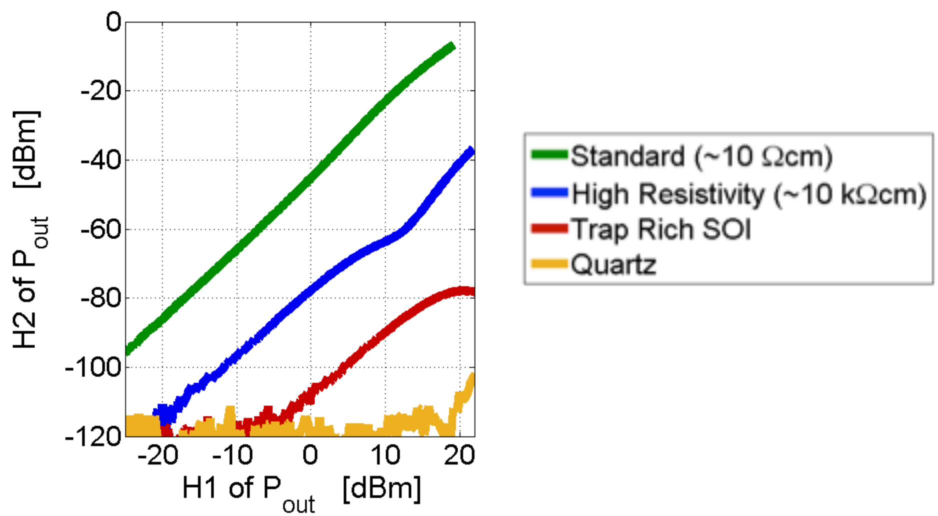
Non-linear signal distortion



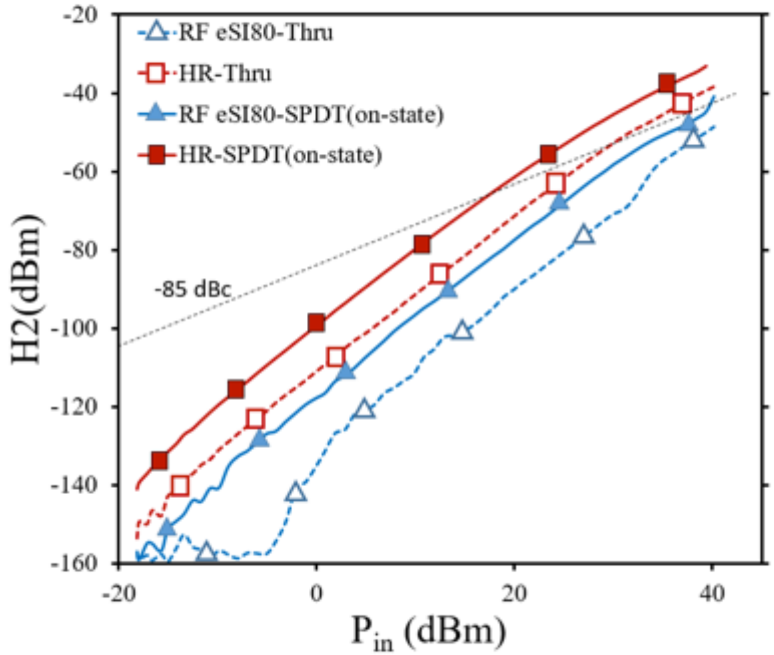
Ideal transfer function: $y = f(x) = a \cdot x$

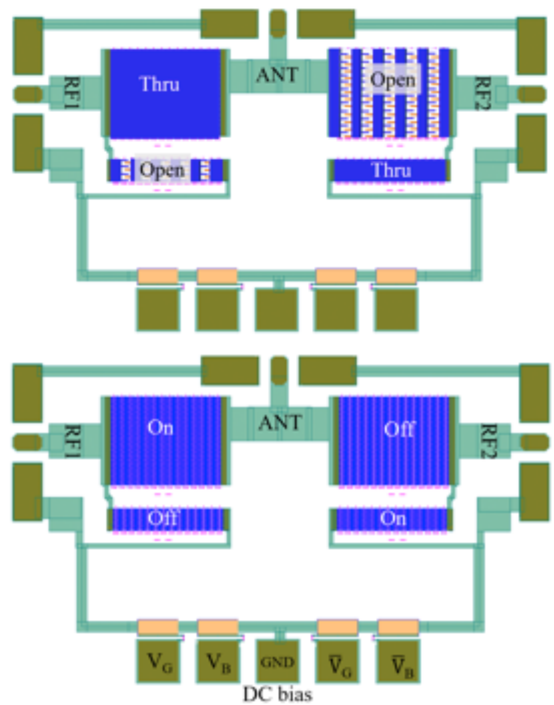
Actual transfer function: $y = f(x) = a \cdot x + b \cdot x^2 + c \cdot x^3 + \ldots$

900 MHz fundamental input

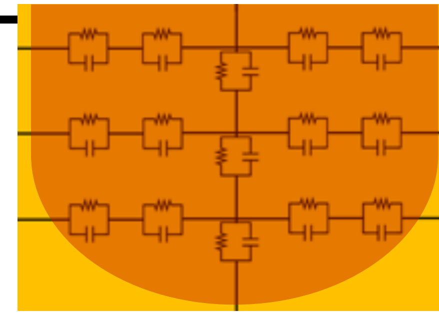


Example: RF switch

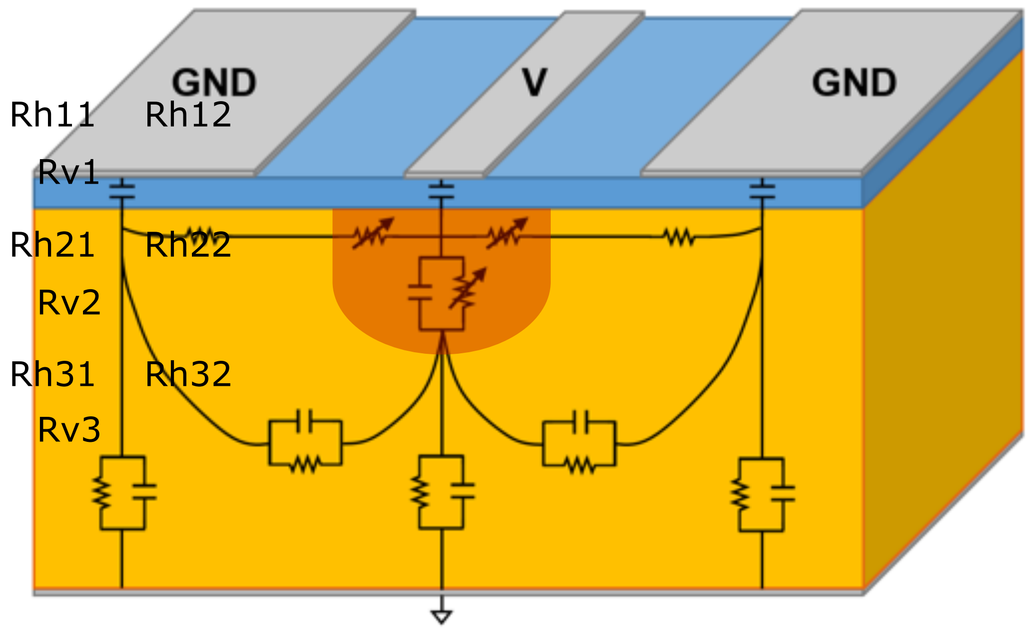




Modeling approach

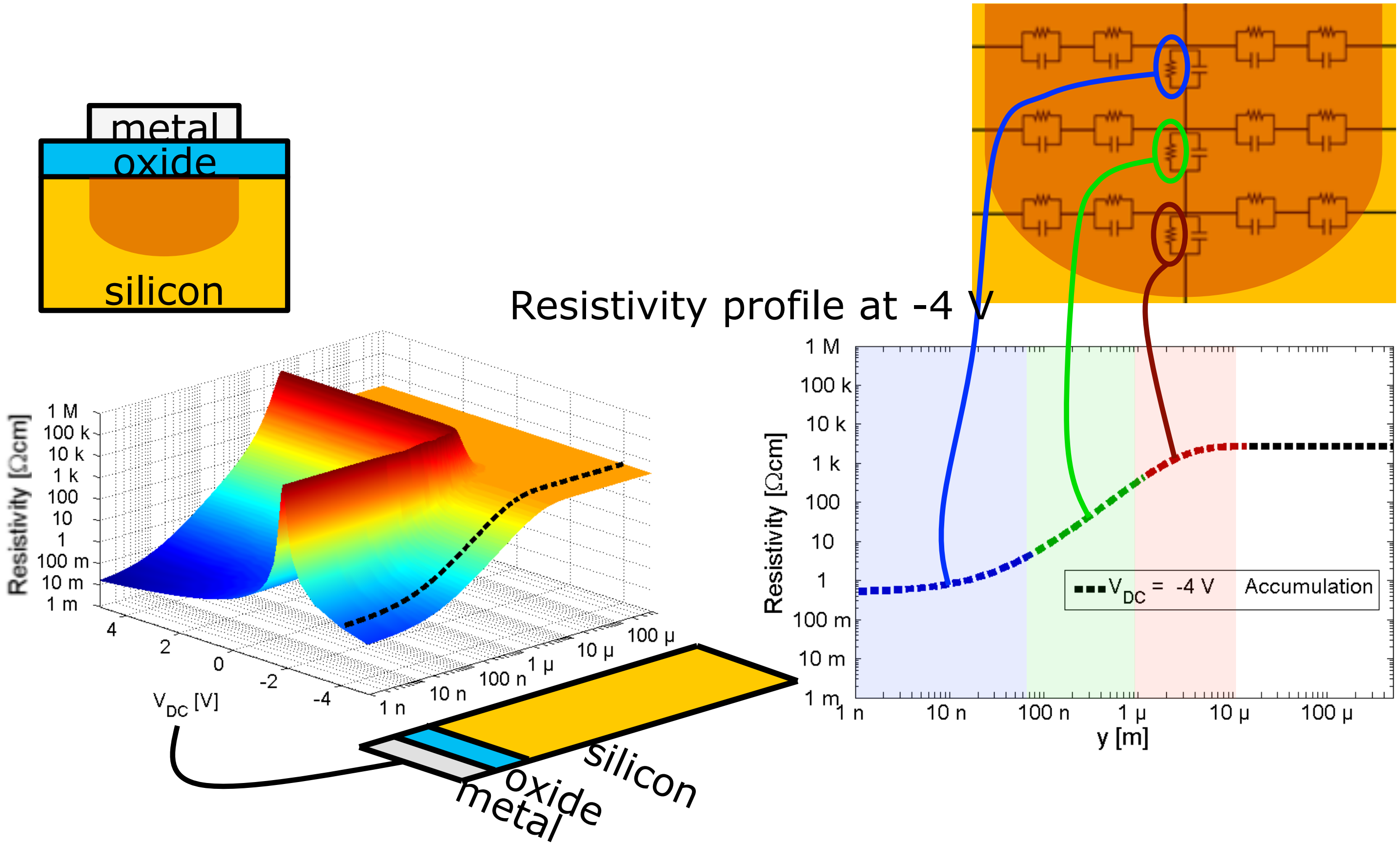


Semiconductors are non-linear by nature!
(Field effect)



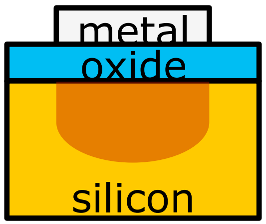
How to model $R(V, t)$?

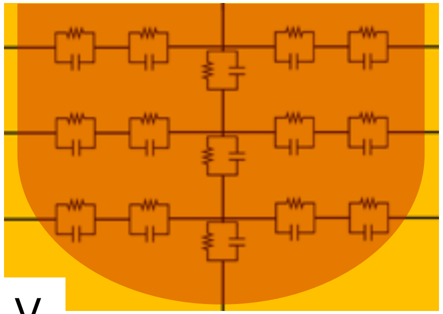
Modeling approach

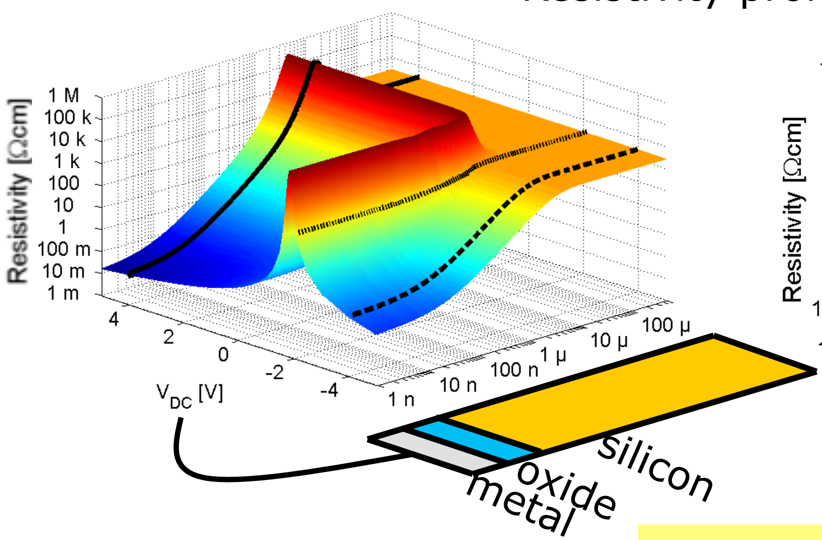


Integration $\int_a^b \ldots \, dy$ → Resistance values at -4 V

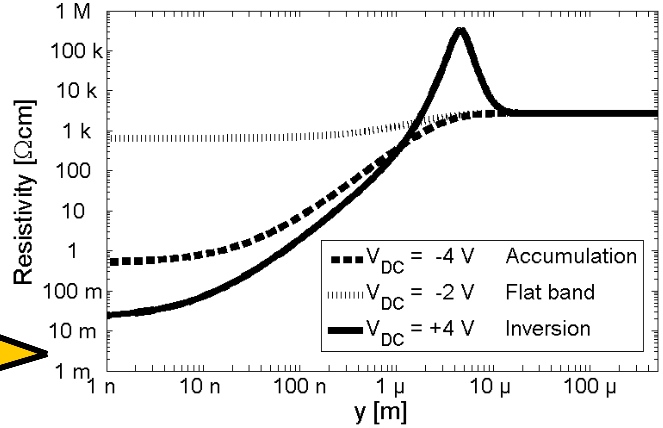
Modeling approach







Resistivity profile at +4 V

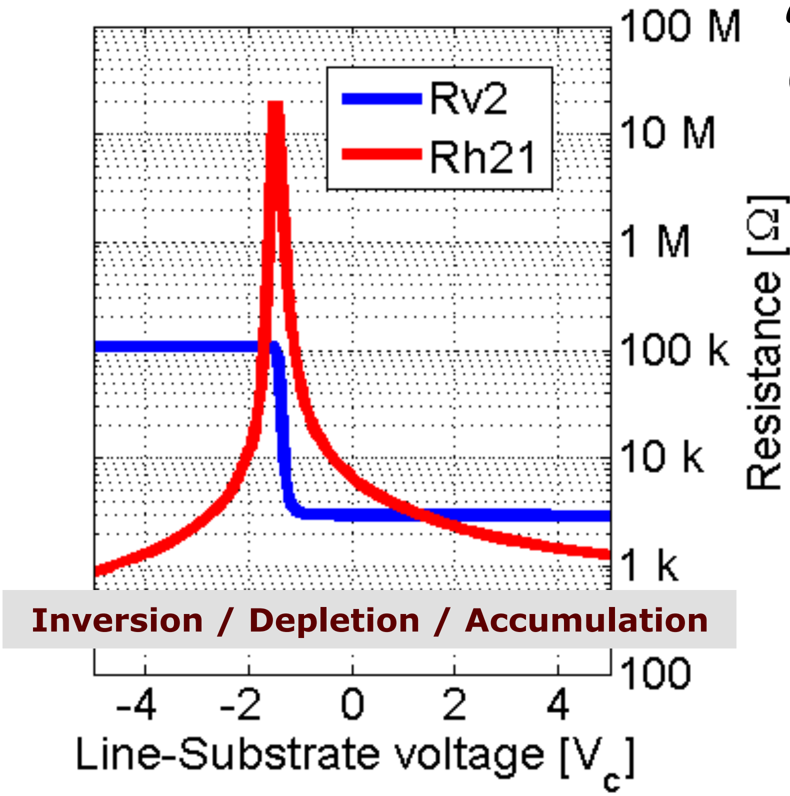


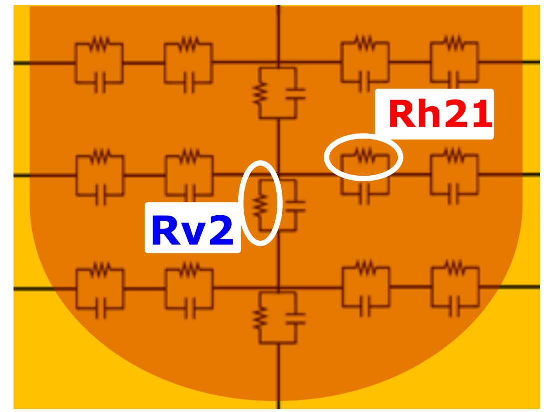
Integration of different curves at other voltages
→ Construct R(V) relationship

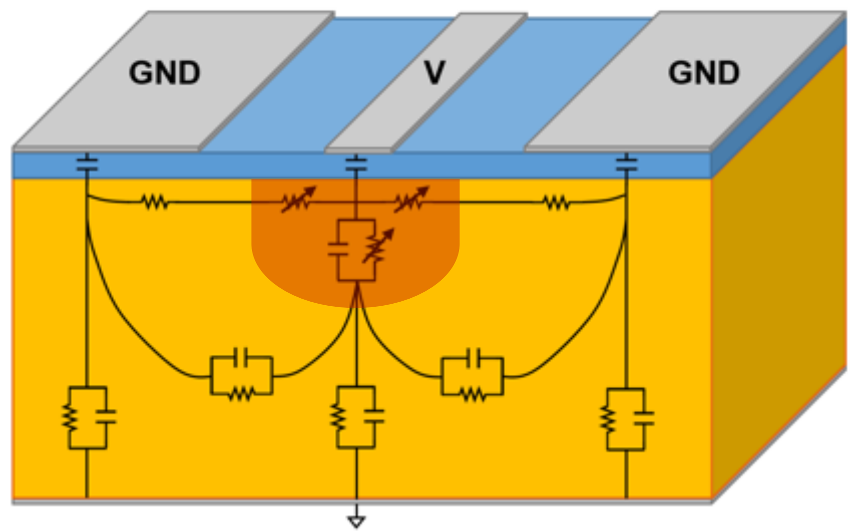
Modeling approach

Construction of R(V) **static** curves:

R↑St at (V)







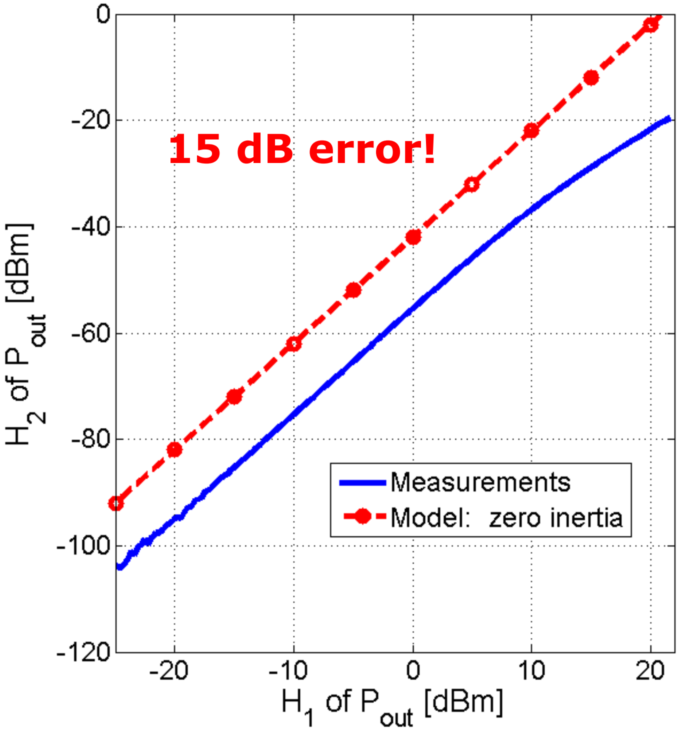
Finite inertia

Let's run our R(V) model…

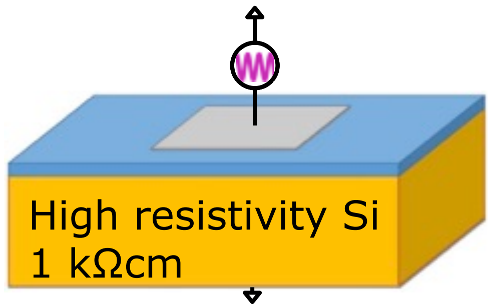
Overestimation of Harmonic Distortion!

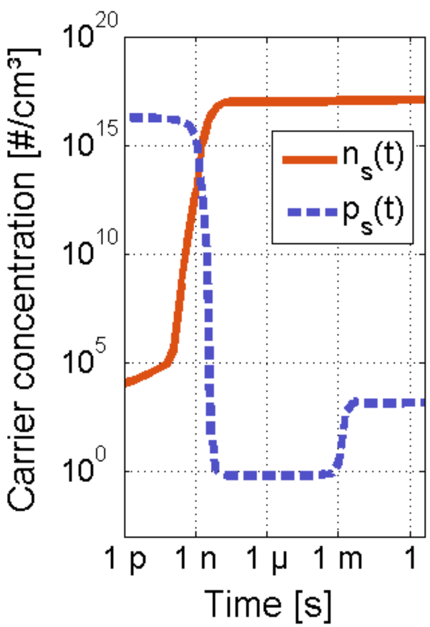
Why?

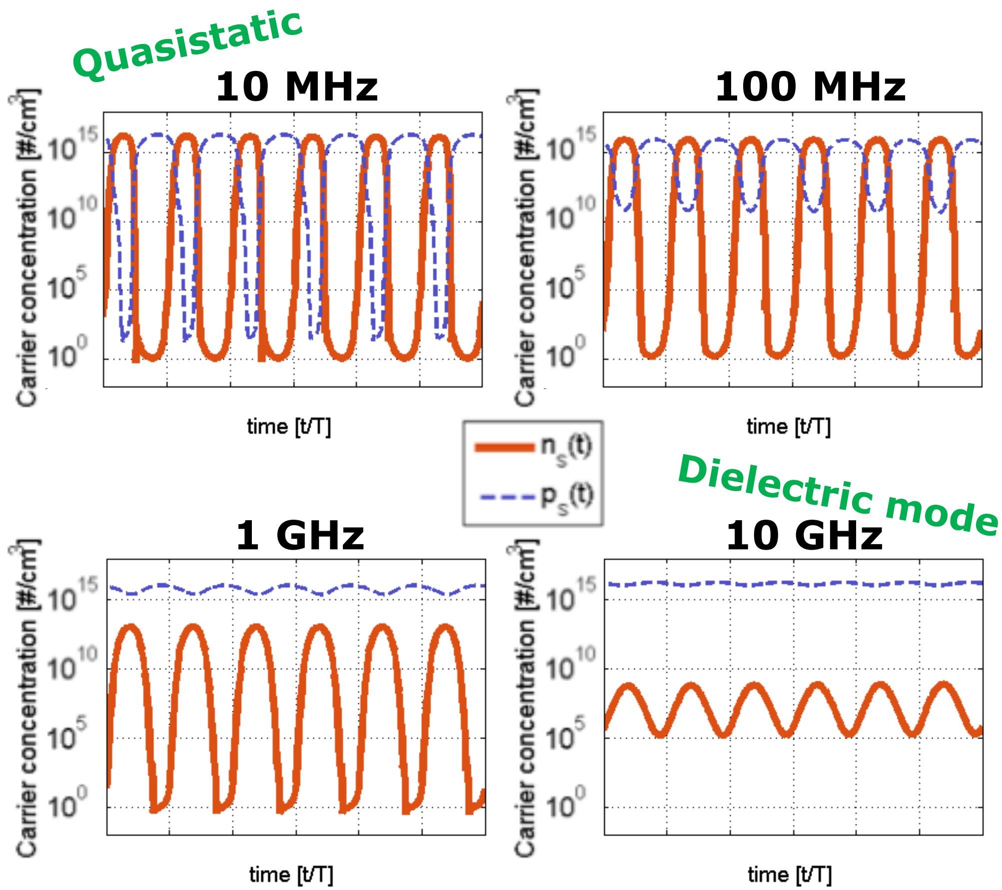
At RF and mm-wave frequencies:
Carriers have some inertia, and a certain finite response time!



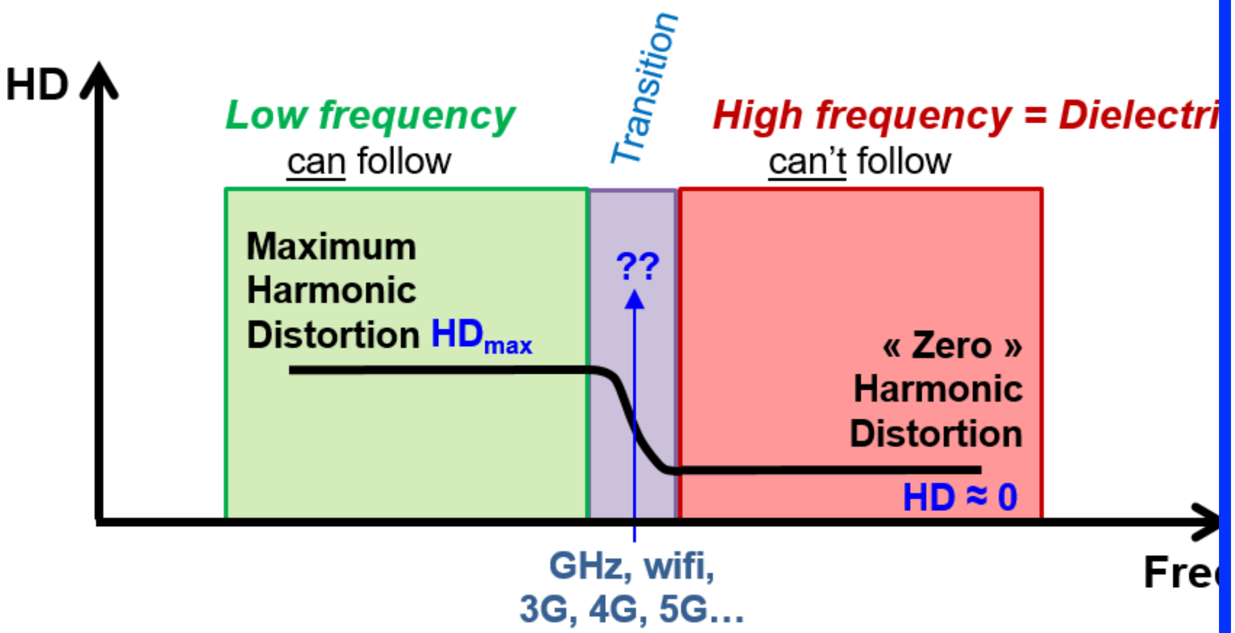
Carrier dynamics and finite inertia



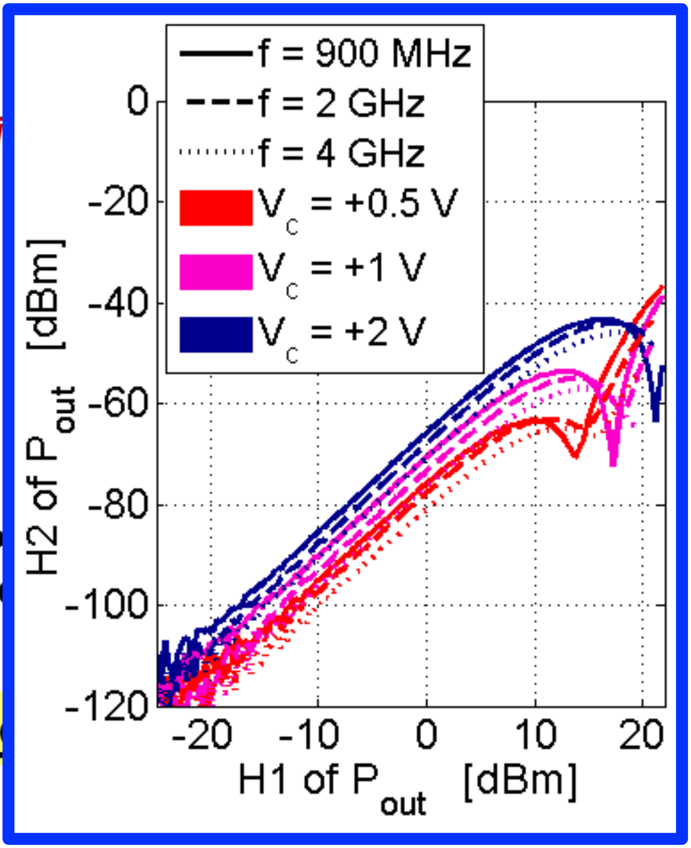




Carrier dynamics and finite inertia



Partial following in the GHz band → model need



Carrier dynamics and finite inertia

When voltage goes from V_i to V_{i+1}

FDTD code

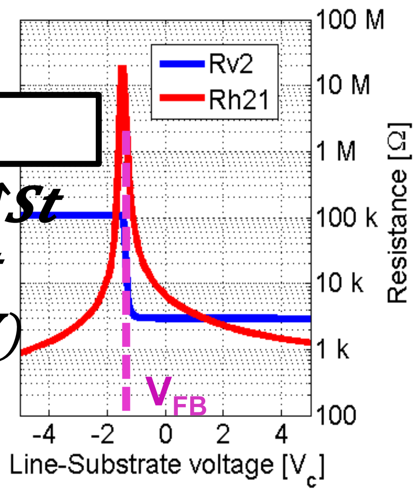
Zero inertia model:

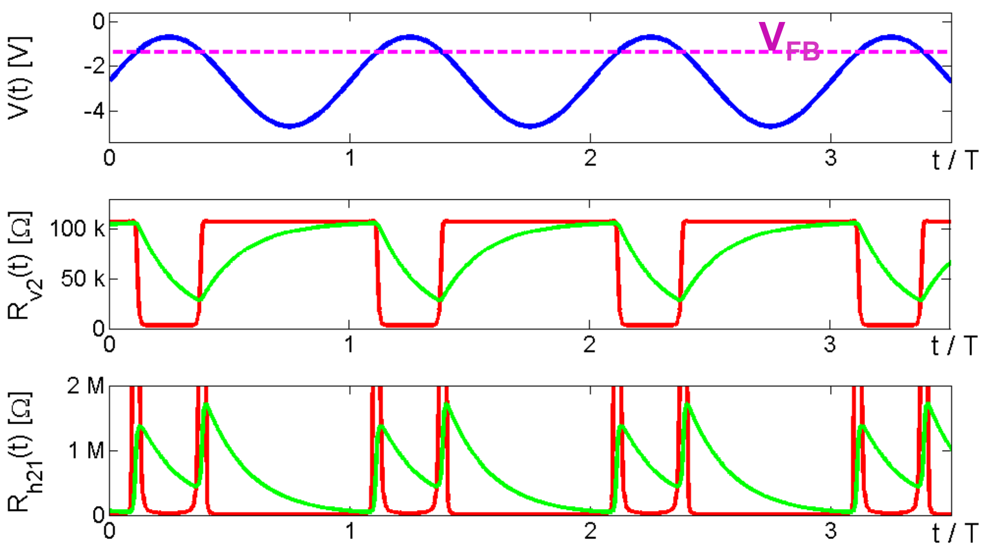
$$R_{i+1} = R^{Stat}(V_{i+1})$$

Finite inertia:

$$R_{i+1} = R^{Stat}(V_{i+1}) - \exp(-\Delta t/\tau)\cdot\left(R^{Stat}(V_{i+1}) - R_i\right)$$

$R^{Stat}(V)$





$\tau \approx 0$ ns

$\tau = 0.5$ ns

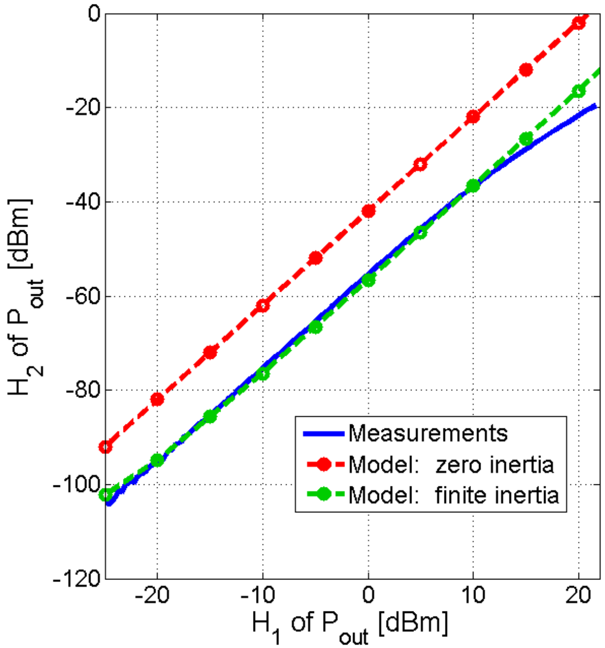
Has time to follow $R(V(t))$ perfectly

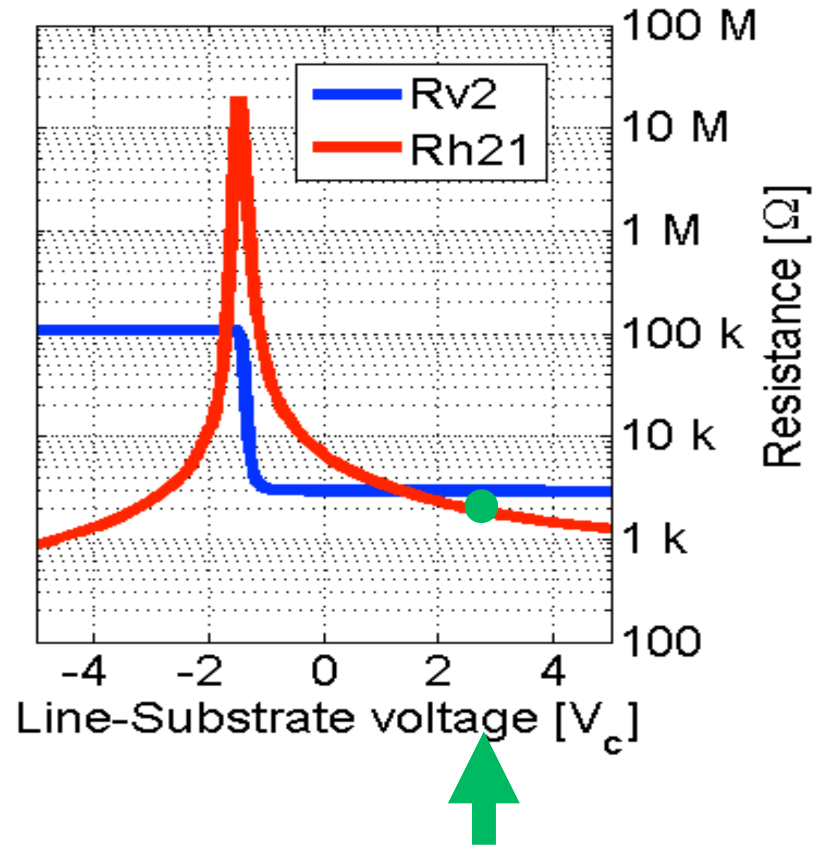
Does not have time to follow $R(V(t))$ perfectly

Carrier dynamics and finite inertia

Introducing a time constant of τ**=1.3 ns**

Simulations no longer overestimated



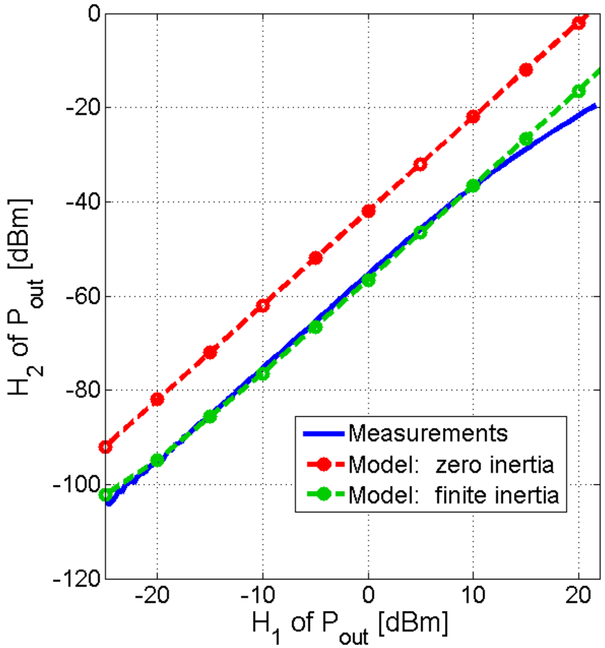


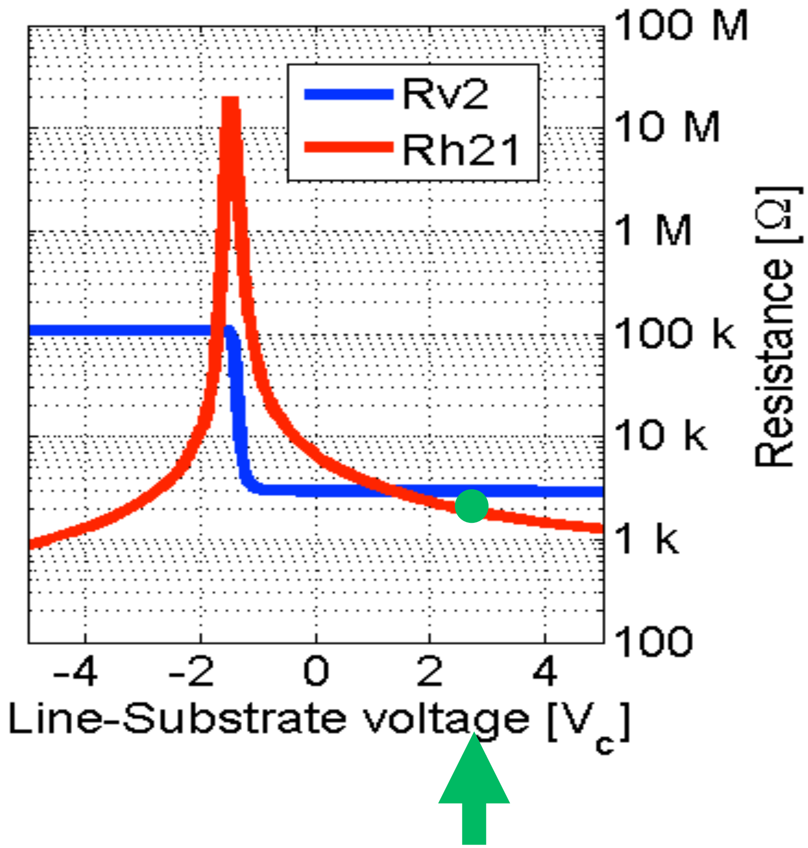
Zero carrier inertia

Carrier dynamics and finite inertia

Introducing a time constant of τ=**1.3 ns**

Simulations no longer overestimated





Finite carrier inertia

Dips and saturations in HD components

A brief history of dips…

- **Our industrial collaborators observed dips in HD**

  …but not very often…

  - ***Measurement error?***
  - ***Weird substrate?***

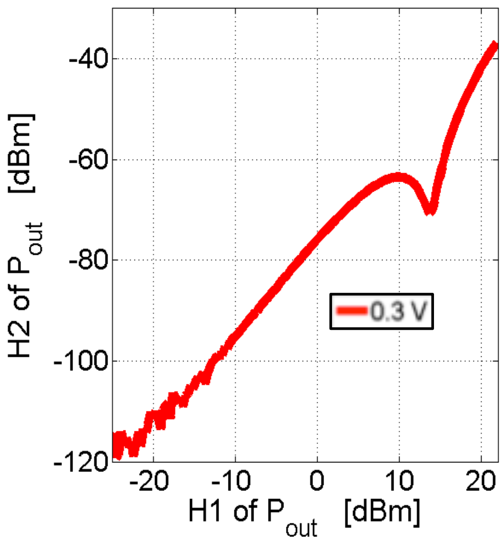
- **Our research group was working on HD modeling, and we had dips!**

  …simulation tool from scratch…

  - ***Bad modeling?***
  - ***Coding bug?***

No error!

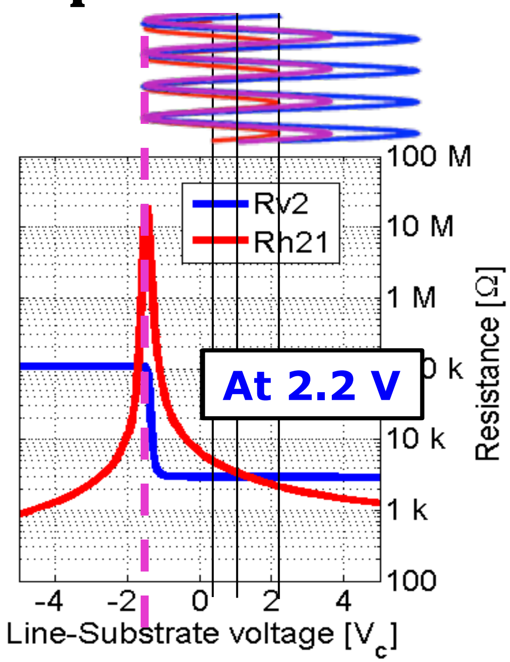
The modeling continued…
- **investigate dips**
- **provide physical insight**

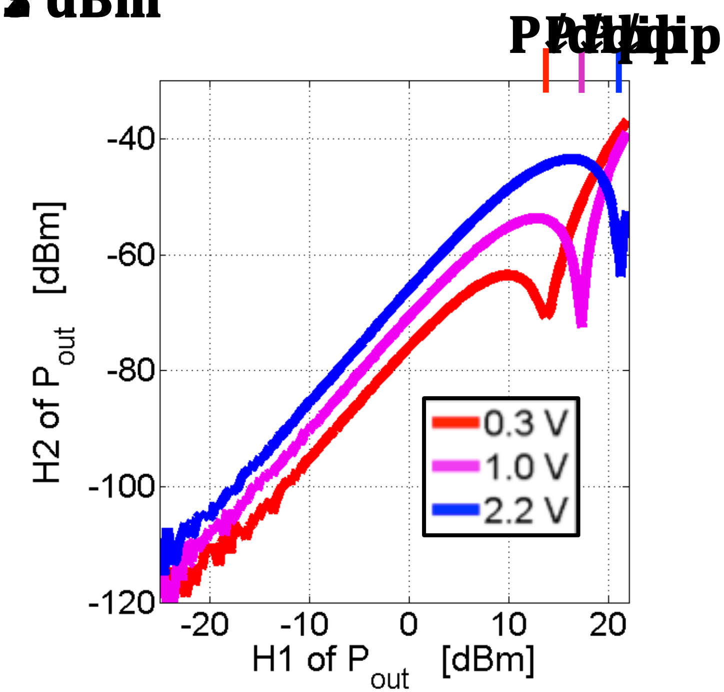


Dips and saturations in HD components

We see a dip when $|V_{DC} - V_{FB}| = A_{dip}$ ***Non-monotonic point***

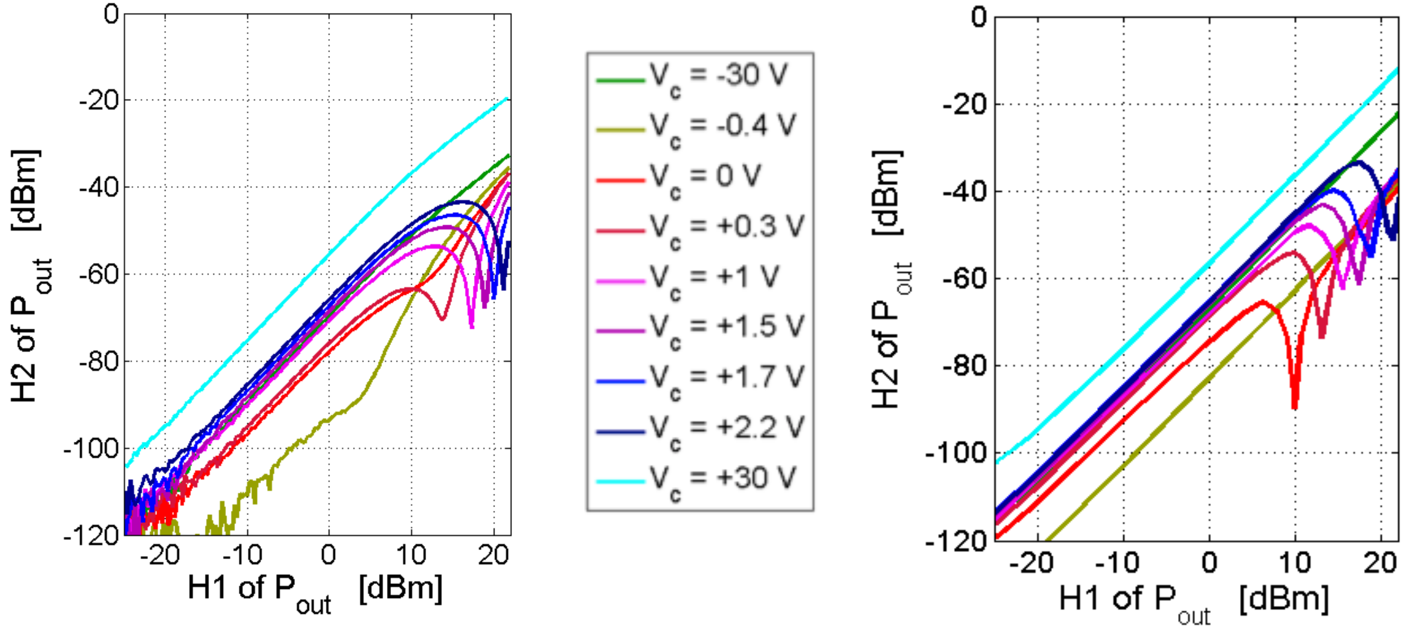
$A_{dip} = 3.6$ V ↔ $P_{dip} = 21.3$ dBm





Dips and saturations in HD components

Measurements **Calibrated simulations**



Good agreement can be achieved

Physical insight into origin of dips

Application

Tune position of dip with a DC bias

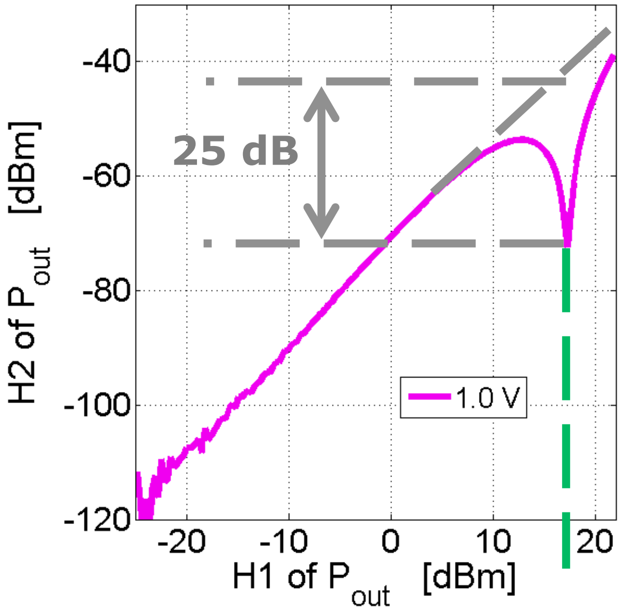
Say you have a circuit that runs **17 dBm** power.

⇒ You should bias DC at +1.0 V to be in the dip !

⇒You gain 25 dB of linearity !

⇒ Possible to track the HD sweet spot with DC biasing

⇒ Patent submitted on this topic



Conclusions

- Electrical properties of substrate are of first importance
  - For small-signal crosstalk levels and RF losses
  - For large-signal distortion
- A variety of tools exist, for different purposes
  - Device physics / EM propagation / Lumped modeling
  - Non-linear substrate modeling is still in its early days…
- Novel modeling of substrate-induced Harmonic Distortion
  - Carrier dynamics taken into account for the first time
  - Dips in harmonic distortion curves
    - Insight into physical origin

Thanks for listening

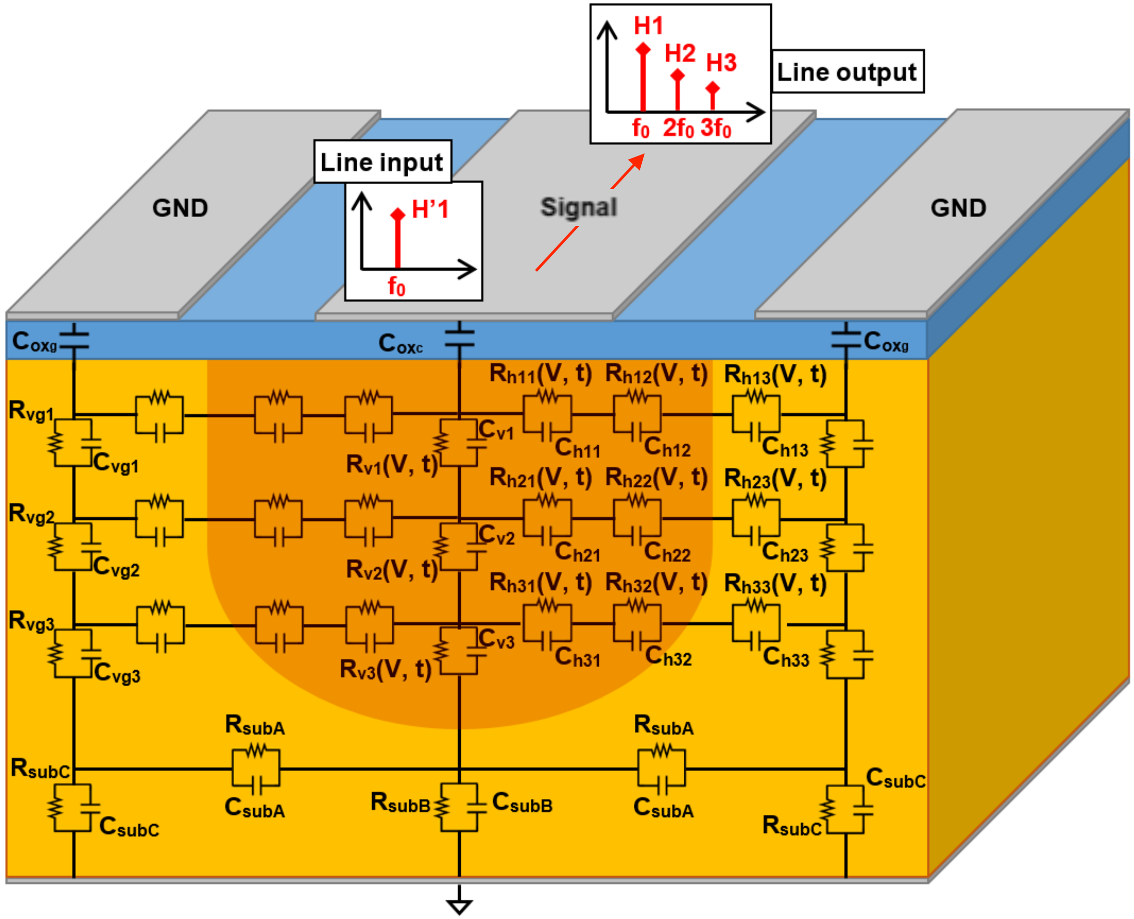
Acknowledgements:

SOITEC, Incize, GlobalFoundries, CWS, TowerJazz

UCL’s technological plateforms Winfab and Welcome

Backup slides

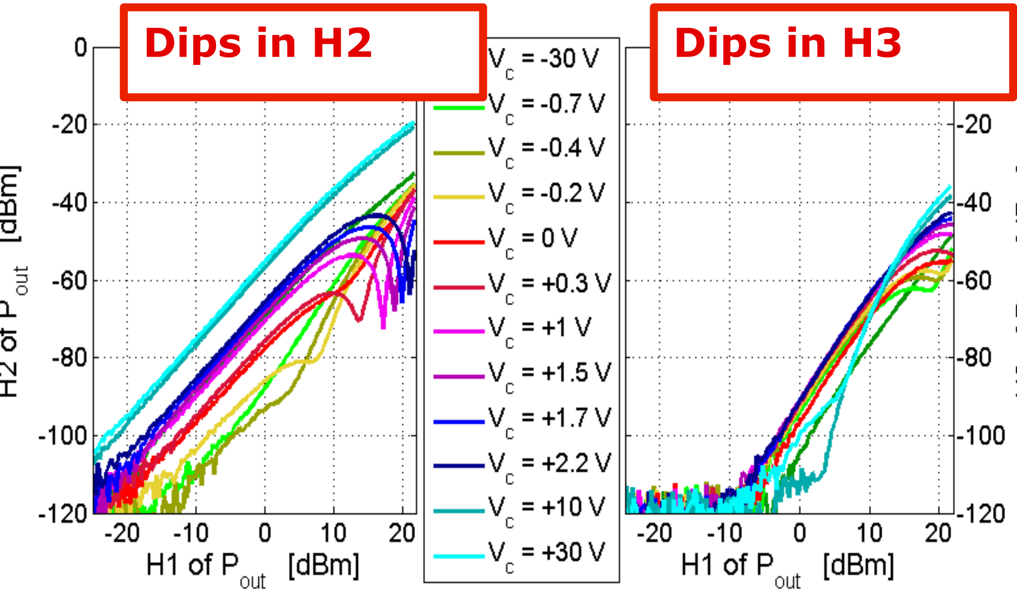
Full model



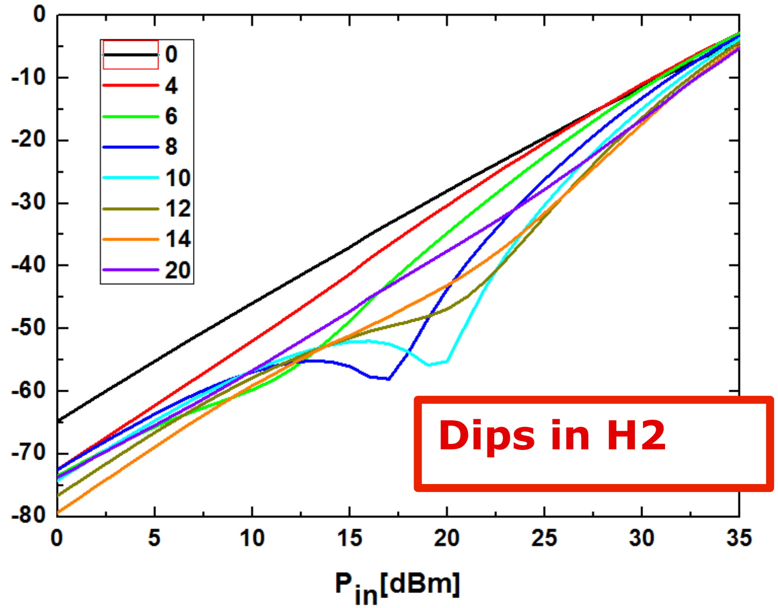
H1
H2
H3
f0 2f0 3f0
Line output
Line input
H'1
f0
GND
Signal
GND
Coxg
Coxc
Coxg
Rh11(V, t) Rh12(V, t) Rh13(V, t)
Rvg1
Cvg1
Cv1
Ch11
Ch12
Ch13
Rv1(V, t)
Rh21(V, t) Rh22(V, t) Rh23(V, t)
Rvg2
Cvg2
Cv2
Ch21
Ch22
Ch23
Rv2(V, t)
Rh31(V, t) Rh32(V, t) Rh33(V, t)
Rvg3
Cvg3
Cv3
Ch31
Ch32
Ch33
Rv3(V, t)
RsubA
RsubA
RsubC
CsubC
CsubA
RsubB
CsubB
CsubA
RsubC
CsubC

Dips on other substrates (1/3)

HR SOI (1)

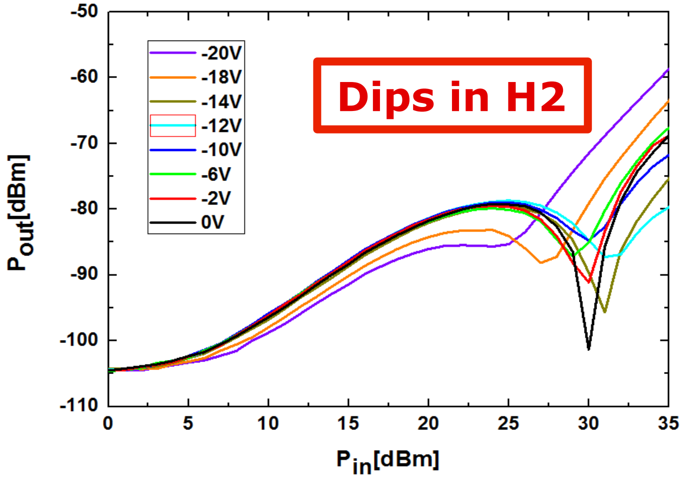


HR SOI (2)

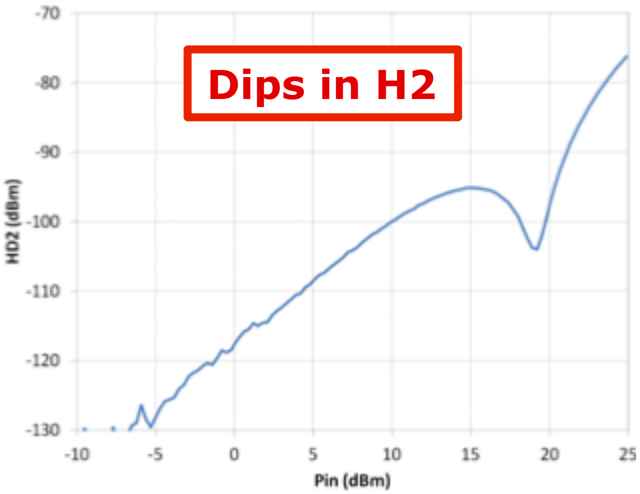


Dips on other substrates (2/3)

TR SOI (1)

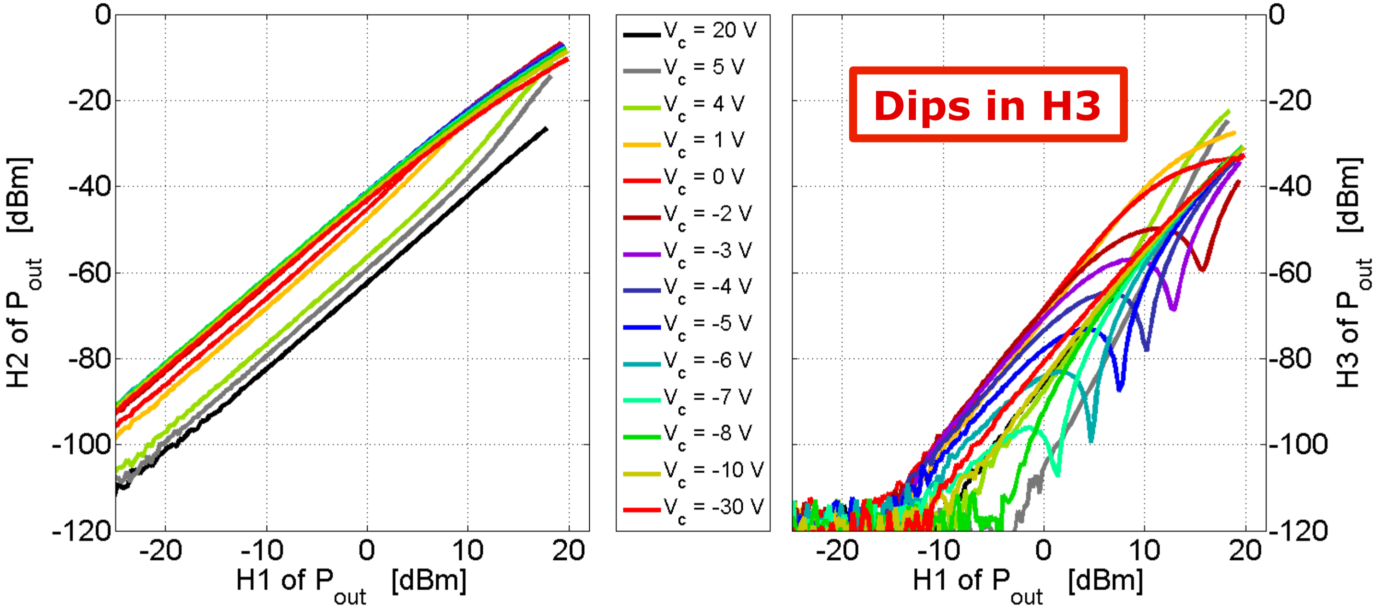


TR SOI (2)



Dips on other substrates (1/3)

Standard resistivity

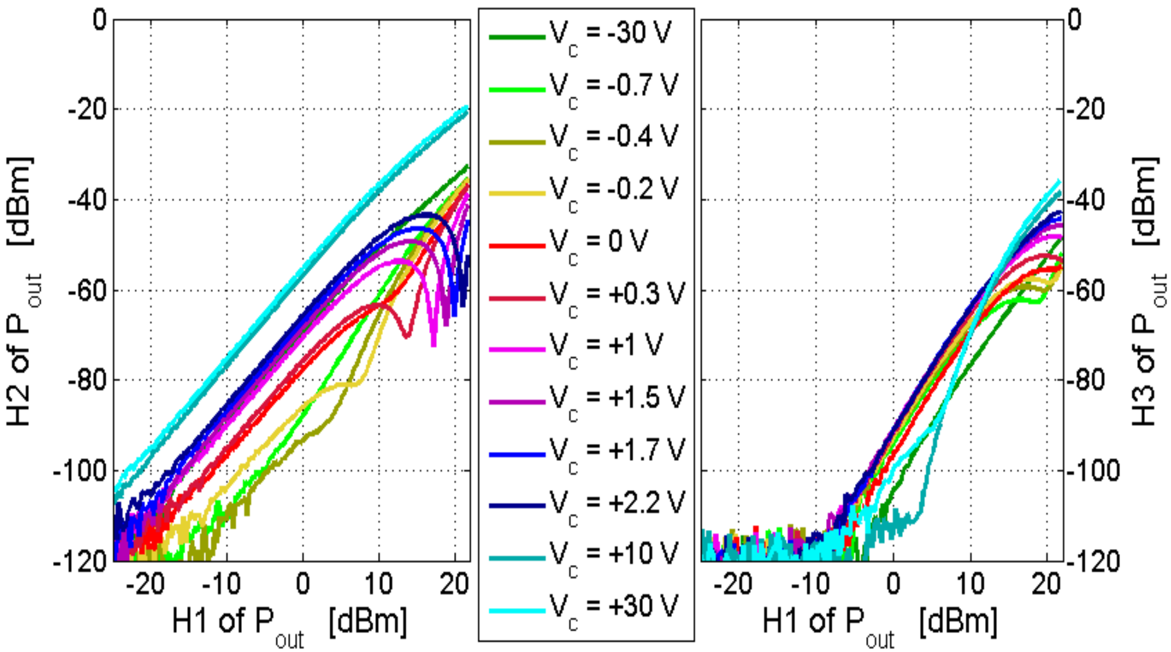


ESSDERC ESSCIRC

Dips are easy to miss!

⇒ **See measurements below.**

⇒ **For a 25 dBm set up we only see the dips is we bias between +0.3 V and +5 V…**



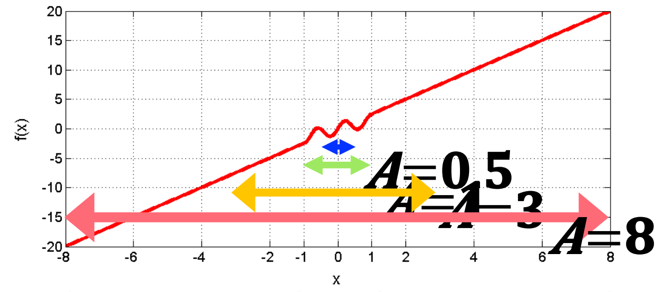
ESSDERC ESSCIRC

Dips and slopes, what does the math say??

We are used to transfer functions being "locally linear" as we zoom in.

⇒ Principle behind *small-signal analysis*

But actually, why not be more linear as we zoom out?

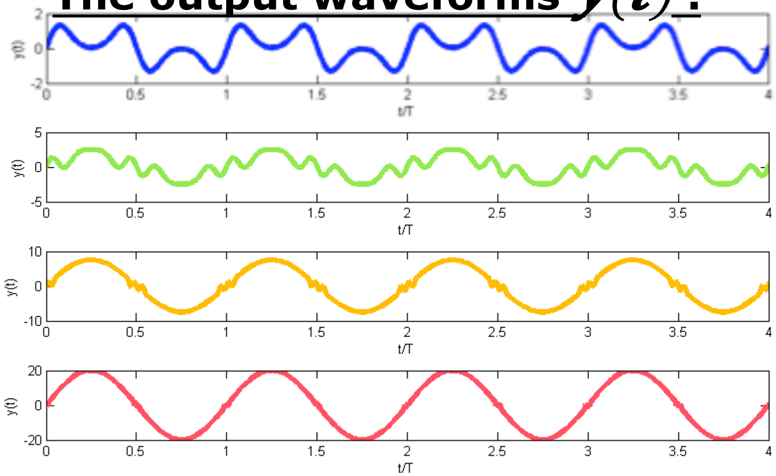


$f(x)$ totally linear between -8 and -1

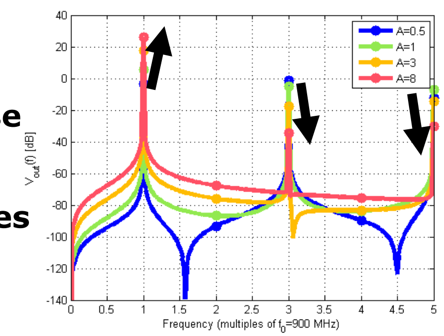
non-linear between -1 and +1

and between +1 and +8

The output waveforms $y(t)$:



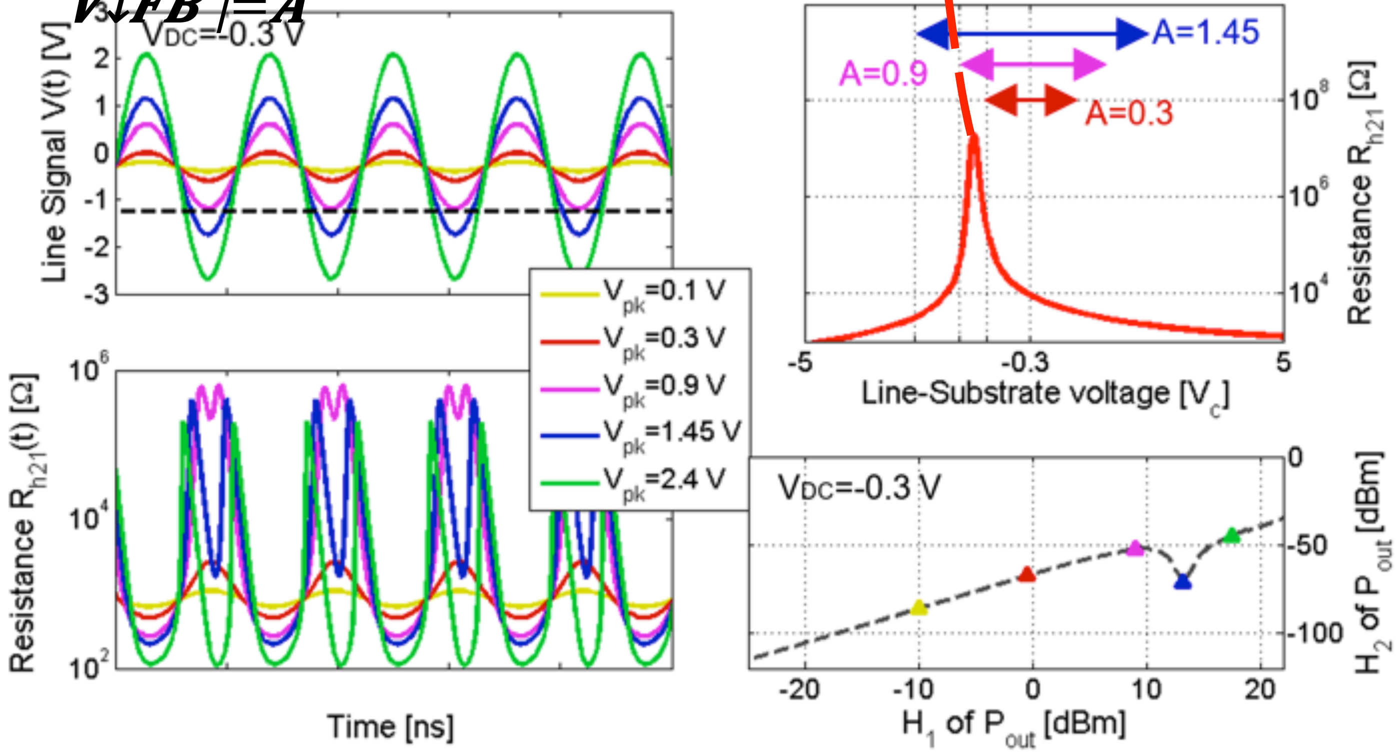
HD decreases as A increases



**Going from small-signal to large signal results in a decrease of the HD!!
(== dip!)**

Time domain resistance analysis (1/2)

We see a dip when $|V_{DC} - V_{FB}| = A$



Time domain resistance analysis (2/2)

The analysis shows that when the RF voltage sweeps through the non-monotonic point, close to the flatband voltage, then the H2 components dips down (blue colored data in all figures).

When the resistance ceases to monotonically increase with the applied voltage, but suddenly decreases over the last part of the negative cycle of the large signal RF voltage wave, this resistance appears more linear because its direction of variation suddenly changes, instead of continuing along the same non-linear trend.