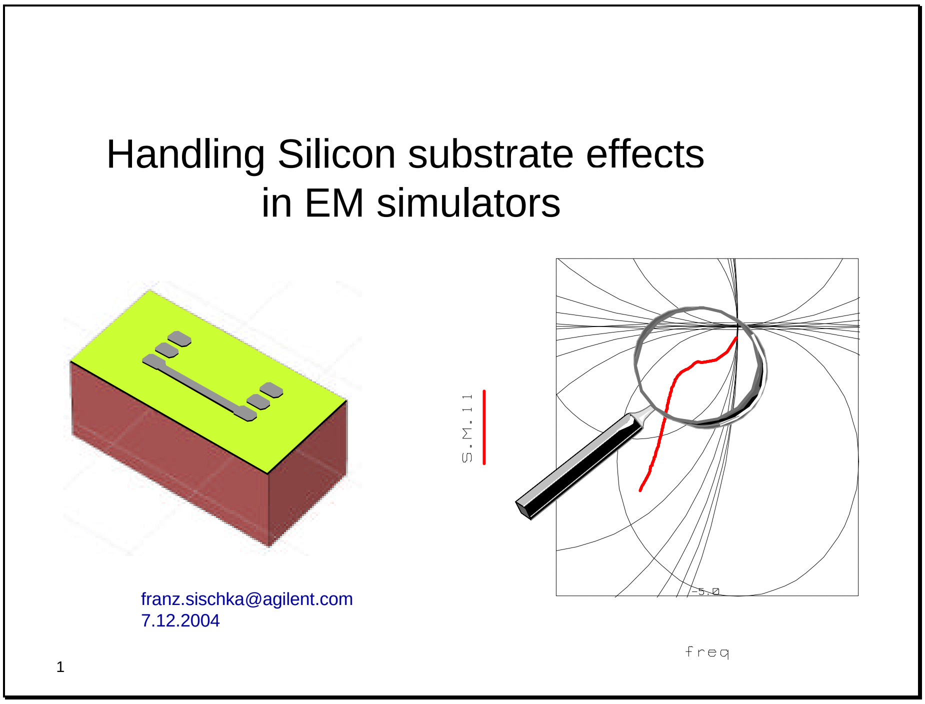
Slide 1



Handling Silicon substrate effects in EM simulators

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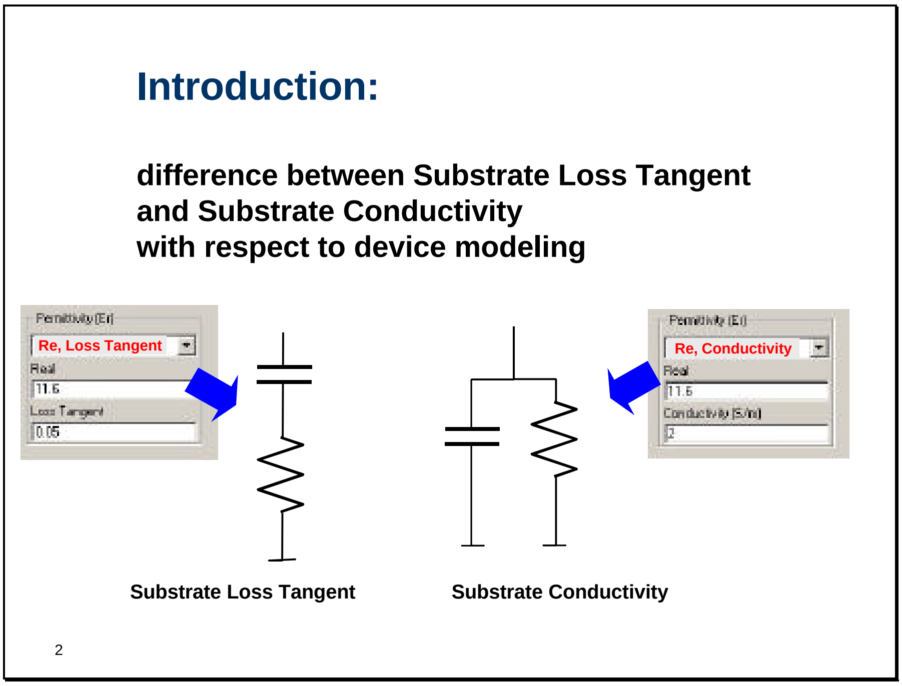
7.12.2004

Slide 2



Introduction:

difference between Substrate Loss Tangent and Substrate Conductivity with respect to device modeling

Permittivity (Er)
Re, Loss Tangent
Real: 11.6
Loss Tangent: 0.05

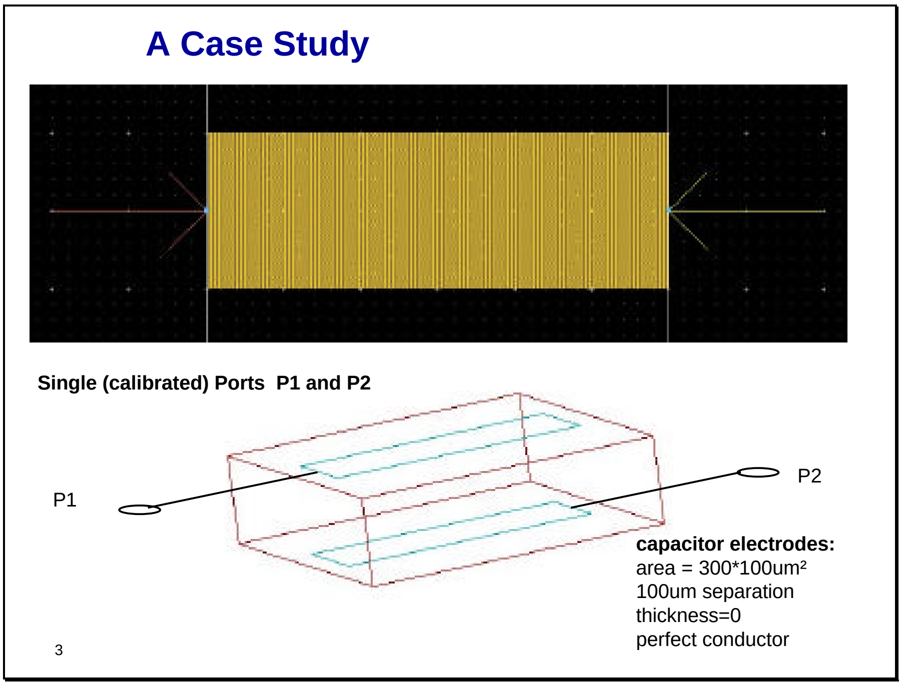
Permittivity (Er)
Re, Conductivity
Real: 11.6
Conductivity (S/m): 2

Substrate Loss Tangent **Substrate Conductivity**

In Momentum, there are 2 ways to specify losses in the substrate:
- eps-r and Loss Tangent
- eps-r and Conductivity

Behind the two choices are two different equivalent schematics.

Slide 3



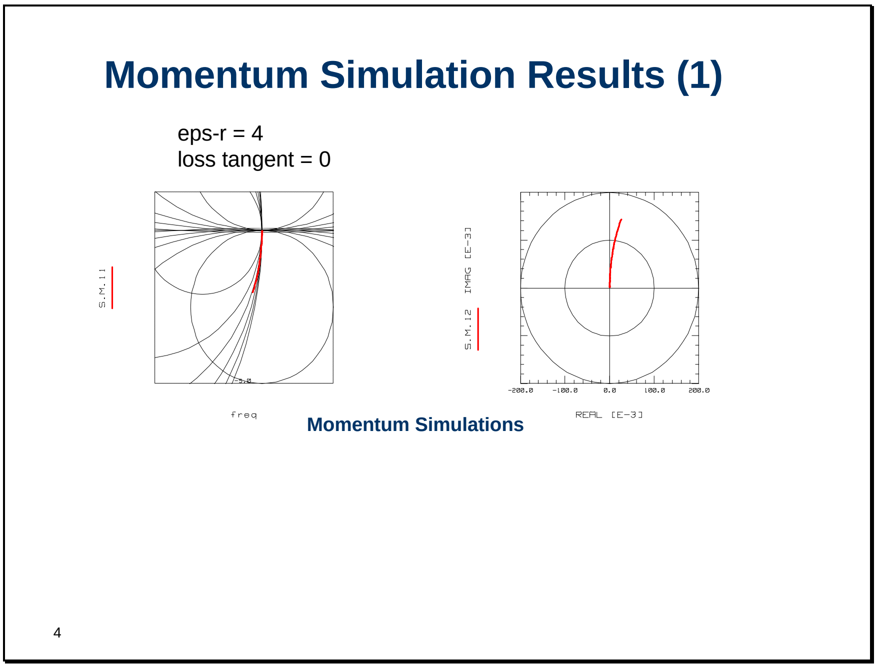
A Case Study

Single (calibrated) Ports P1 and P2

capacitor electrodes:
area = 300*100um²
100um separation
thickness=0
perfect conductor

We begin with a little case study on a very simple structure: a piece of substrate between two ideal metal plates. Each metal plate serves as an S-parameter port. We apply here the Momentum Single Ports, which represent calibrated ports.

Slide 4



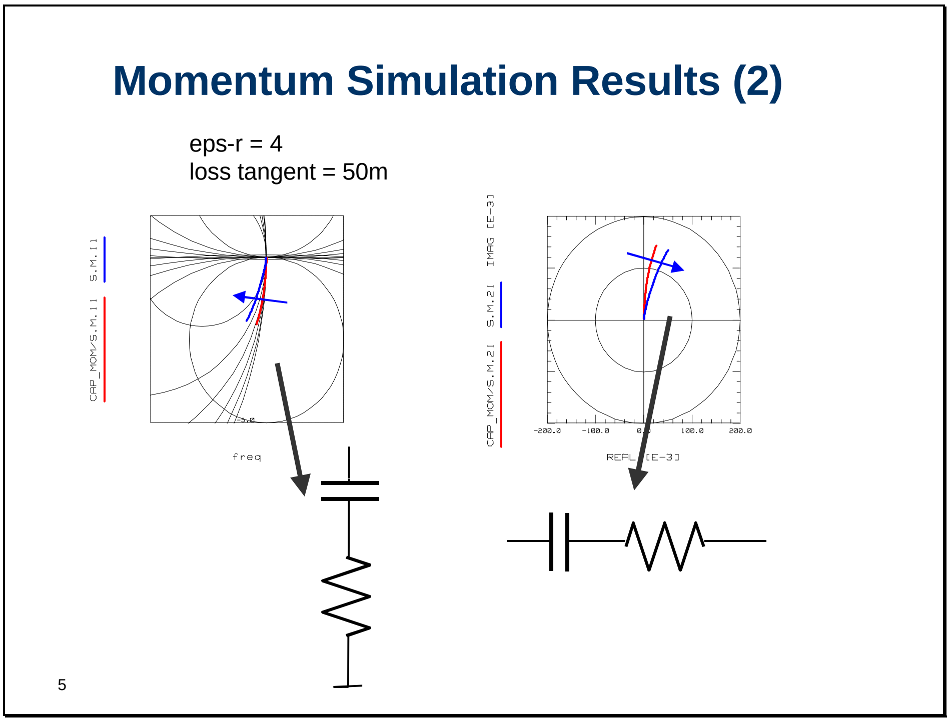
Momentum Simulation Results (1)

eps-r = 4
loss tangent = 0

Momentum Simulations

As a starting point, we get the Sxx and Sxy for eps-r=4 and no substrate losses. This will be the reference curves.

Slide 5

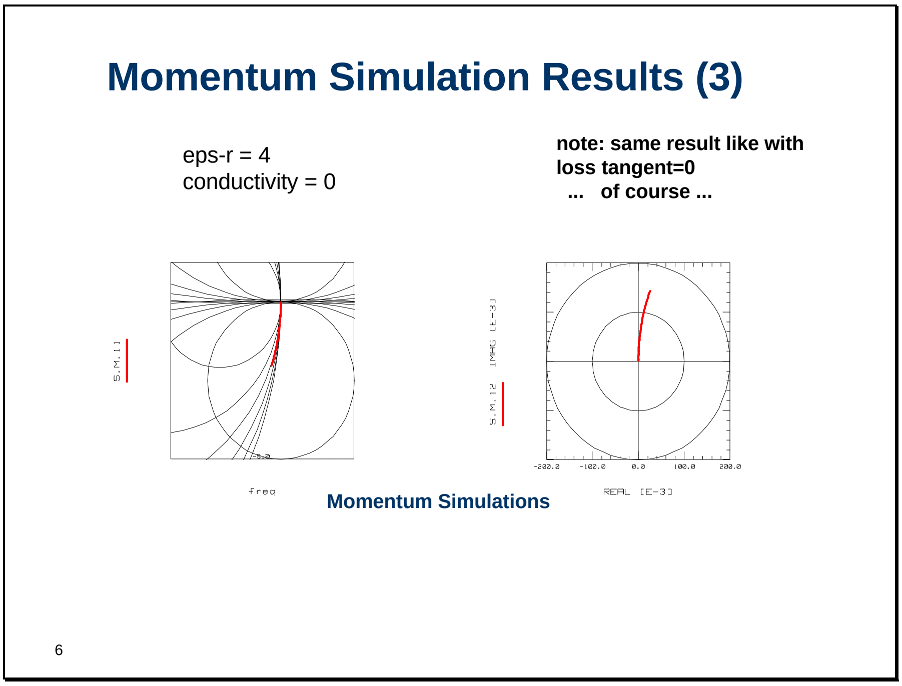


Momentum Simulation Results (2)

eps-r = 4
loss tangent = 50m

Specifying a loss tangent of 50m, we see that the starting point of Sxx is not affected, but its end point towards infinite frequency is affected. This means that the underlying schematic is represented by a C in series with a R. And R represents the loss tangent.

Slide 6



Momentum Simulation Results (3)

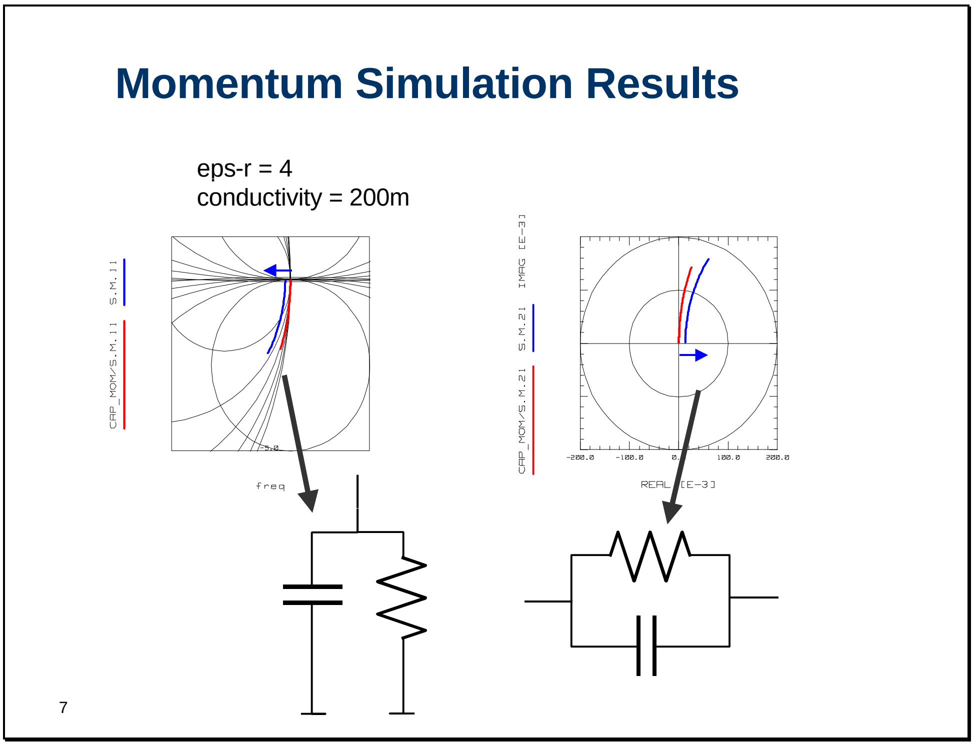
eps-r = 4
conductivity = 0

note: same result like with loss tangent=0
... of course ...

Momentum Simulations

Now, we investigate the effect of conductivity. To commence, we have conductivity=0 in the slide above.

Slide 7

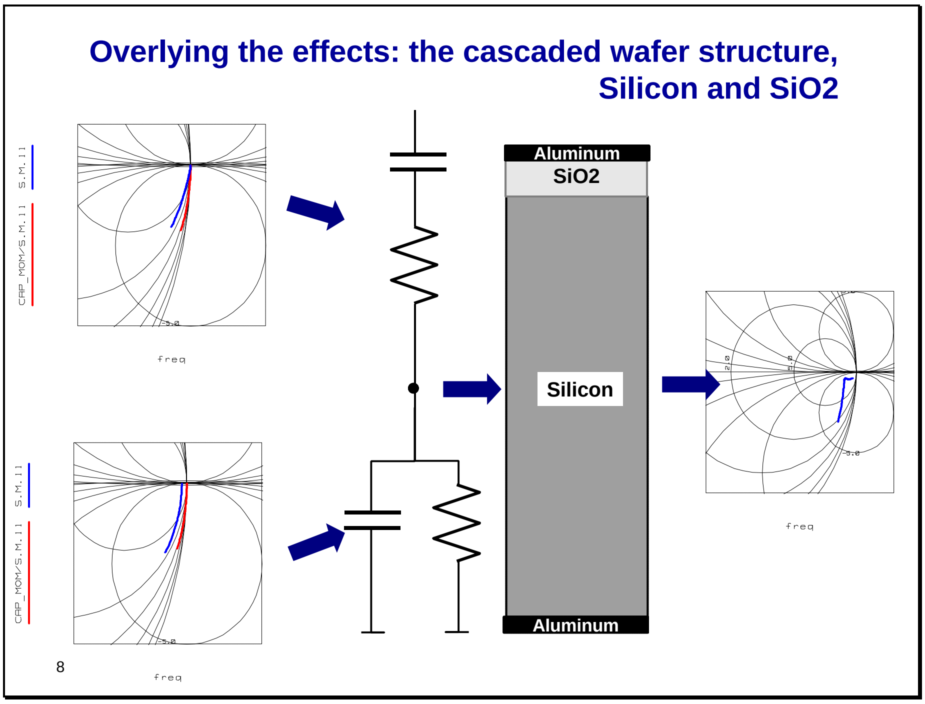


Momentum Simulation Results

eps-r = 4
conductivity = 200m

Specifying conductivity=200m, we see that the starting point of Sxx is now affected, but its end point for infinite frequency still tends towards 0 Ohm. This means that the underlying schematic is represented by a C in parallel with a R. And R represents the conductivity.

Slide 8

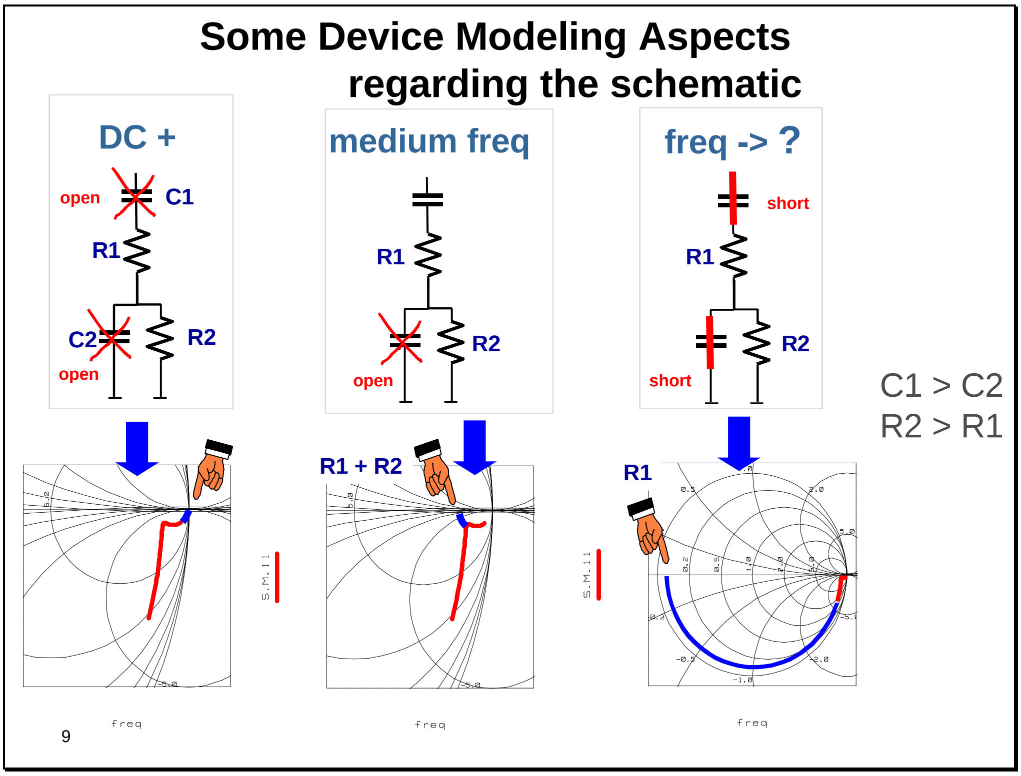


Overlying the effects: the cascaded wafer structure, Silicon and SiO2

Aluminum
SiO2
Silicon
Aluminum

We can now overlay these two effects and end up with a silicon structure as shown above, and a resulting Sxx curve.

Slide 9

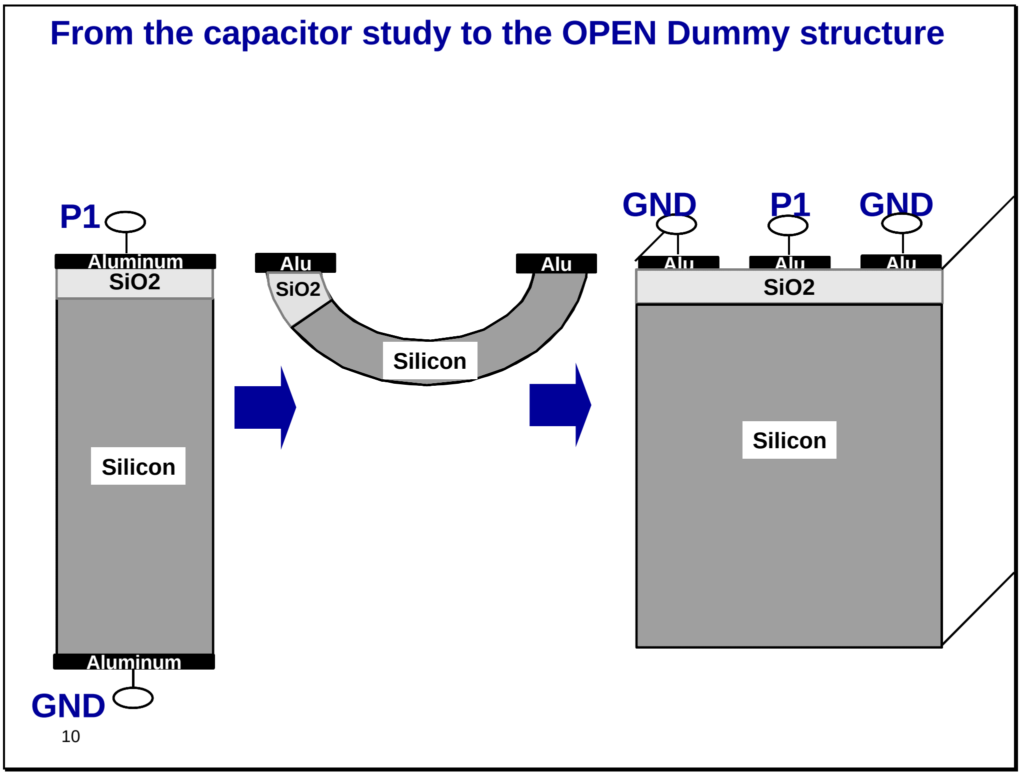


Some Device Modeling Aspects regarding the schematic

C1 > C2
R2 > R1

The slide above re-emphases the interpretation of the metal-SIO2-Si-metal schematic, from DC to infinite frequency, from a modeling engineer's standpoint.

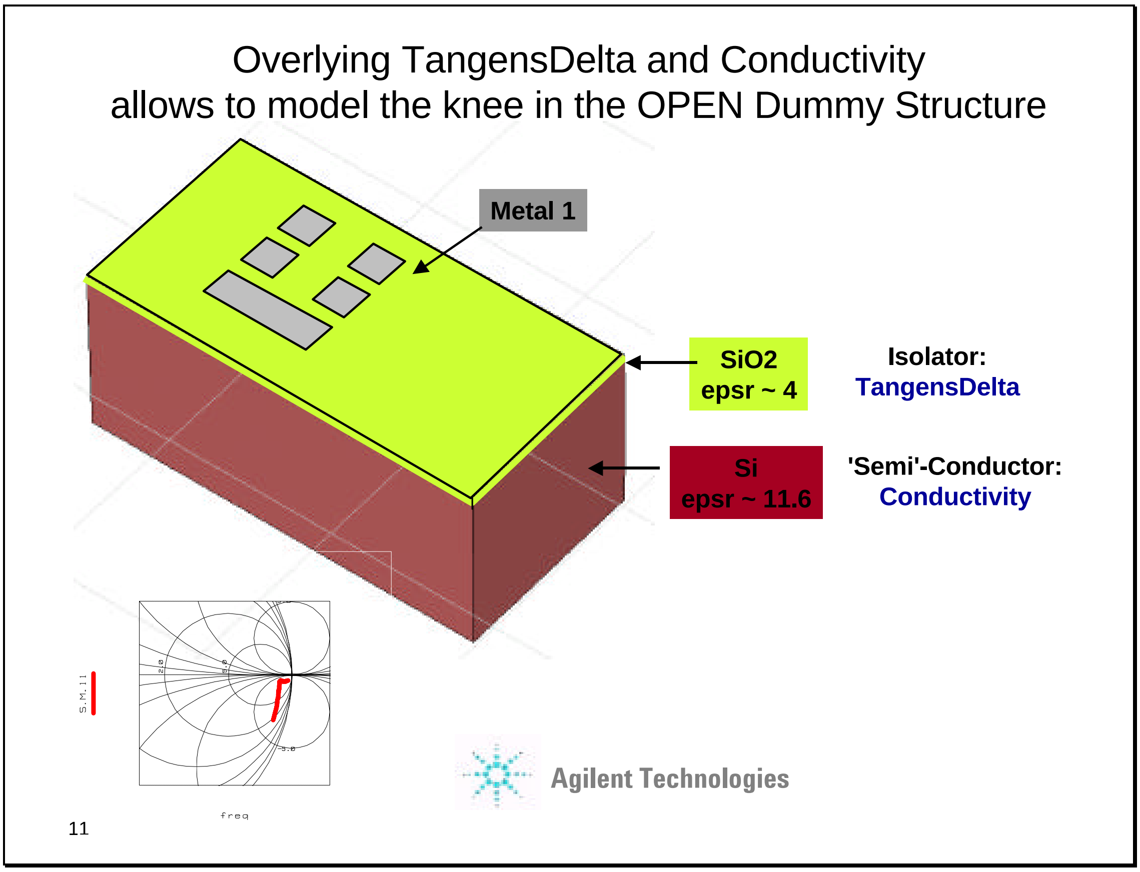
Slide 10



From the capacitor study to the OPEN Dummy structure

Now, we bend the SiO2-Si structure and end up with the GSG-contacted (Ground-Signal-Ground) pad structure for Port1 and Port2 of typical on-wafer measurements.

Slide 11



Overlying TangensDelta and Conductivity allows to model the knee in the OPEN Dummy Structure

Metal 1

SiO2
epsr ~ 4

Isolator:
TangensDelta

Si
epsr ~ 11.6

'Semi'-Conductor:
Conductivity

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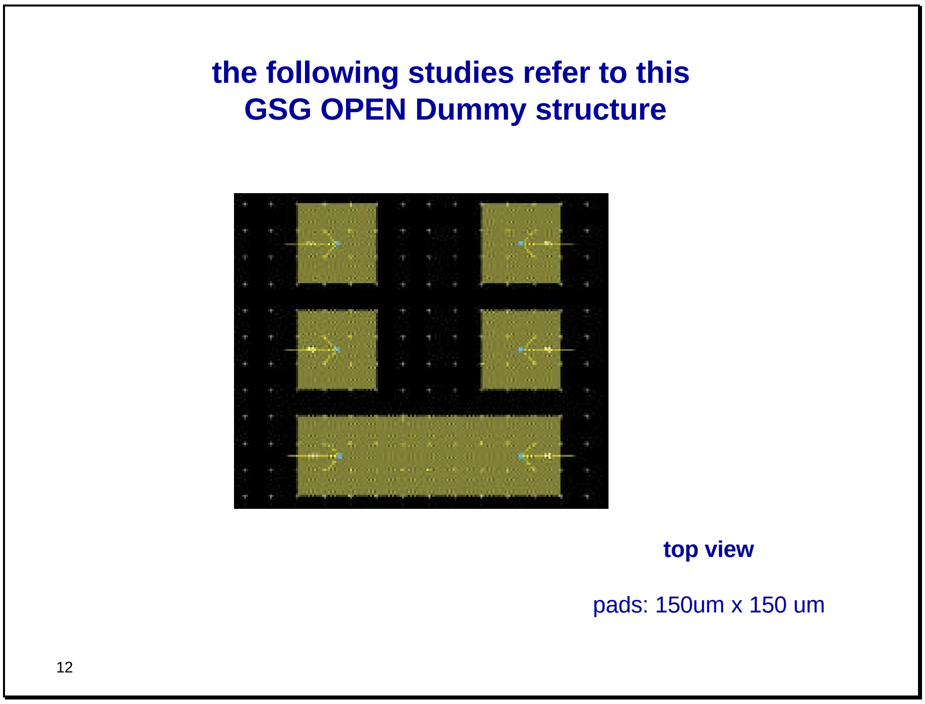
We are now ready to discuss the right settings and optimization/tuning steps for the substrate parameters in Momentum.
We will start with a typical OPEN Dummy structure as depicted above.
Slide 12

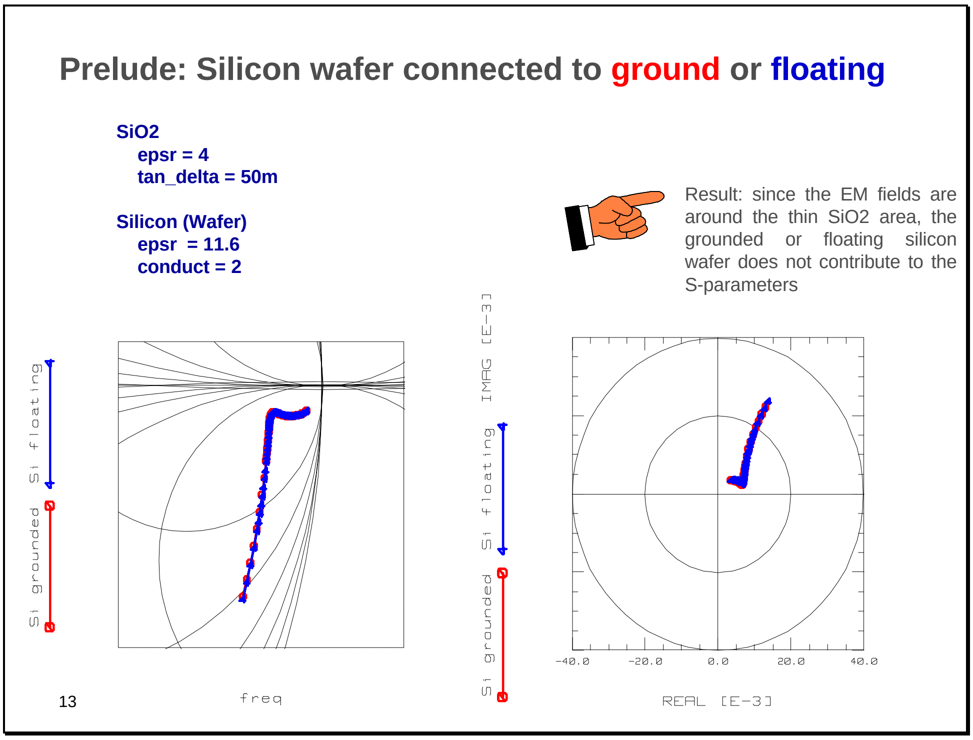


the following studies refer to this GSG OPEN Dummy structure

top view

pads: 150um x 150 um

Slide 13



Prelude: Silicon wafer connected to ground or floating

SiO2
epsr = 4
tan_delta = 50m

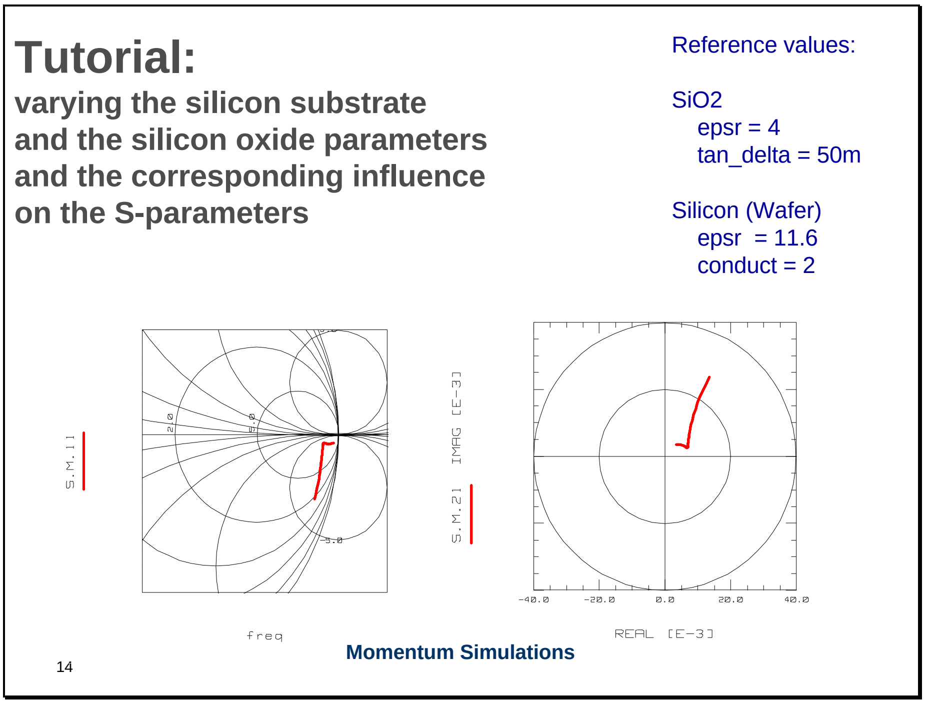
Silicon (Wafer)
epsr = 11.6
conduct = 2

Result: since the EM fields are around the thin SiO2 area, the grounded or floating silicon wafer does not contribute to the S-parameters

13

As a first experiment, we check if there is an influence of a floating chuck (wafer) compared to a grounded chuck. Since the EM-fields are 'around' the GSG structure in metal1, and if we keep in mind that a typical wafer thickness is 0.5mm .. 0.8mm, and the SiO2 thickness is 0.5um .. 0.8um, it becomes clear that the ground contact of the chuck is neglectible for our further considerations.

Slide 14



Tutorial:

varying the silicon substrate and the silicon oxide parameters and the corresponding influence on the S-parameters

Reference values:

SiO2
epsr = 4
tan_delta = 50m

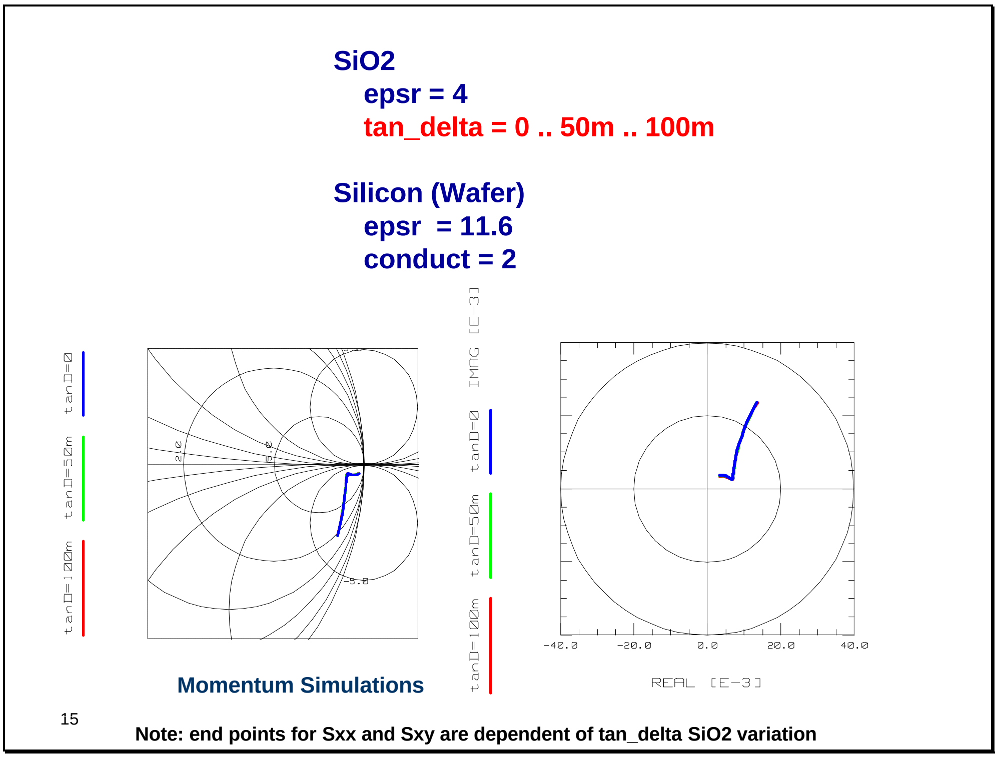
Silicon (Wafer)
epsr = 11.6
conduct = 2

Momentum Simulations

14

The substrate parameters shown above and the resulting Sxx and Sxy plots are the reference for our further investigations.

Slide 15



SiO2
epsr = 4
tan_delta = 0 .. 50m .. 100m

Silicon (Wafer)
epsr = 11.6
conduct = 2

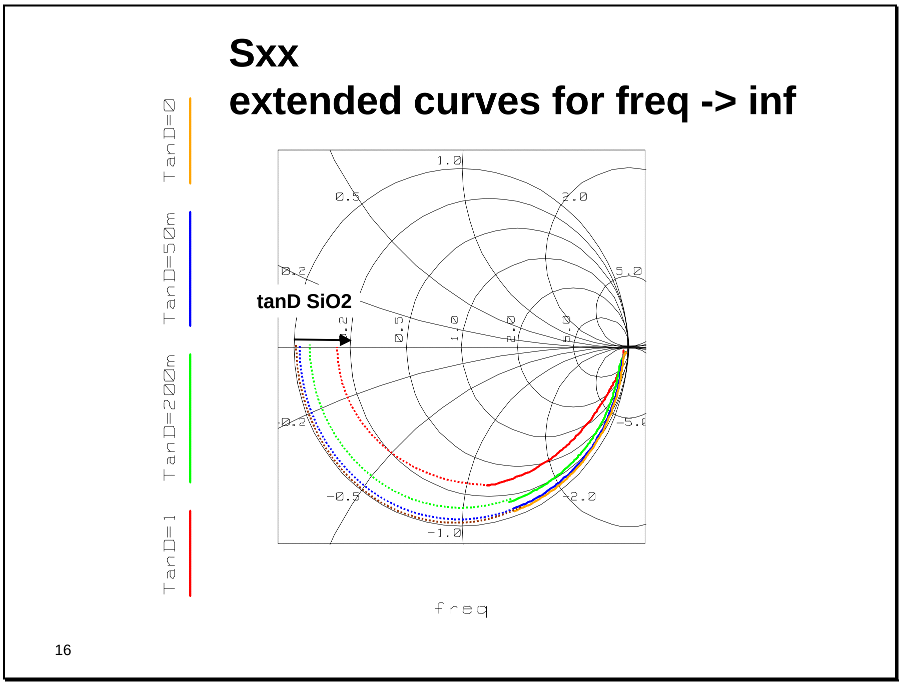
Momentum Simulations

15

Note: end points for Sxx and Sxy are dependent of tan_delta SiO2 variation

Varying the losses of the SiO2 does not exhibit an influence for small frequencies.

Slide 16



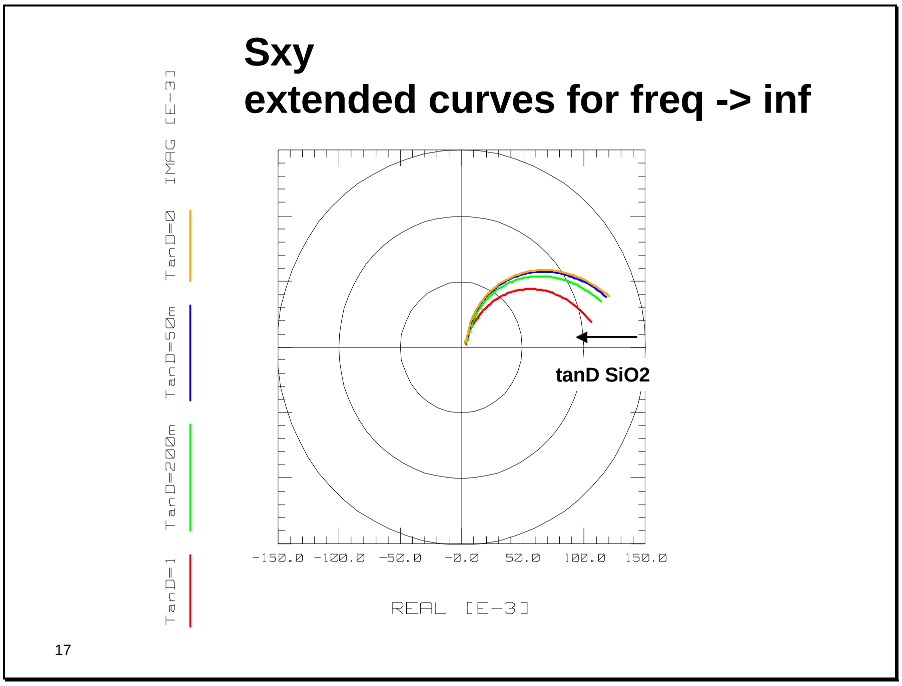
Sxx
extended curves for freq -> inf

tanD SiO2

16

However, as expected, the losses (tangens delta) in the SiO2 show up for infinite frequencies.

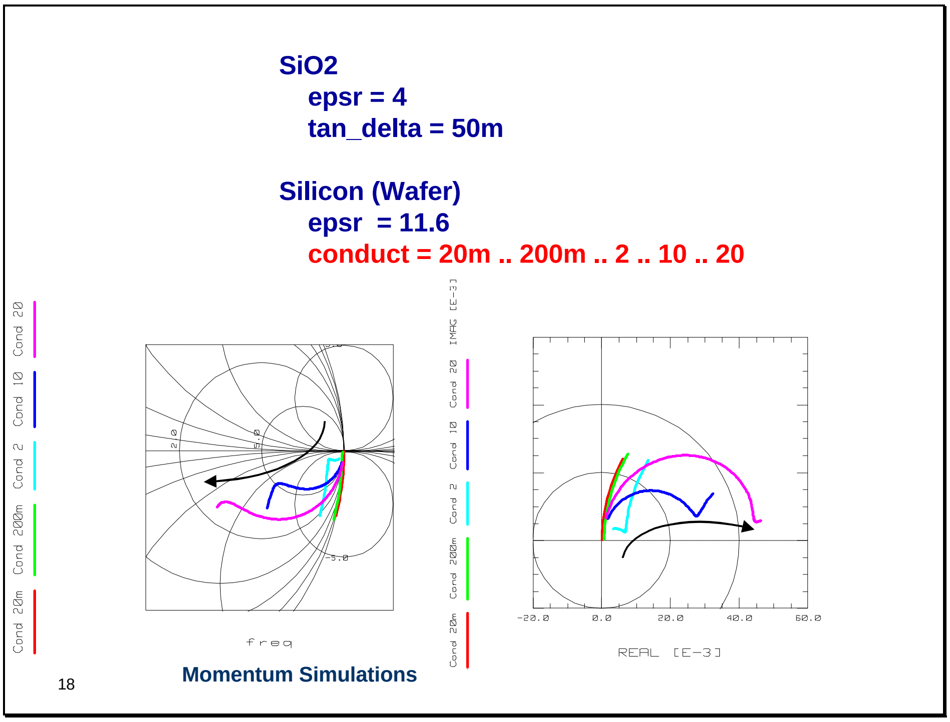
Slide 17



Sxy
extended curves for freq -> inf

tanD SiO2

Slide 18



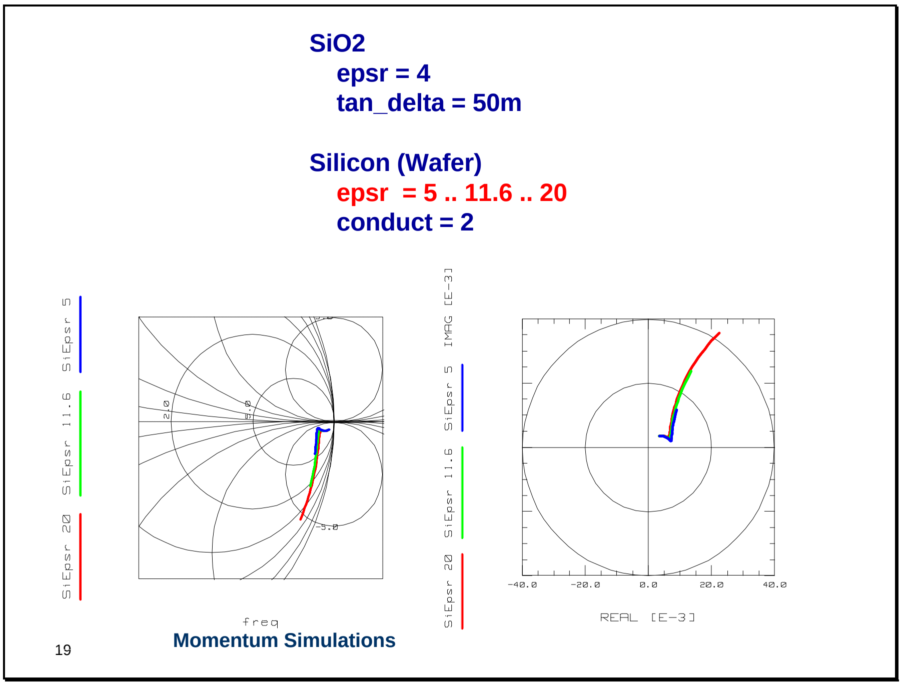
SiO2
epsr = 4
tan_delta = 50m

Silicon (Wafer)
epsr = 11.6
conduct = 20m .. 200m .. 2 .. 10 .. 20

Momentum Simulations

As expected, the conductivity of the silicon wafer material determines the knee in the Sxx and Sxy plots.

Slide 19



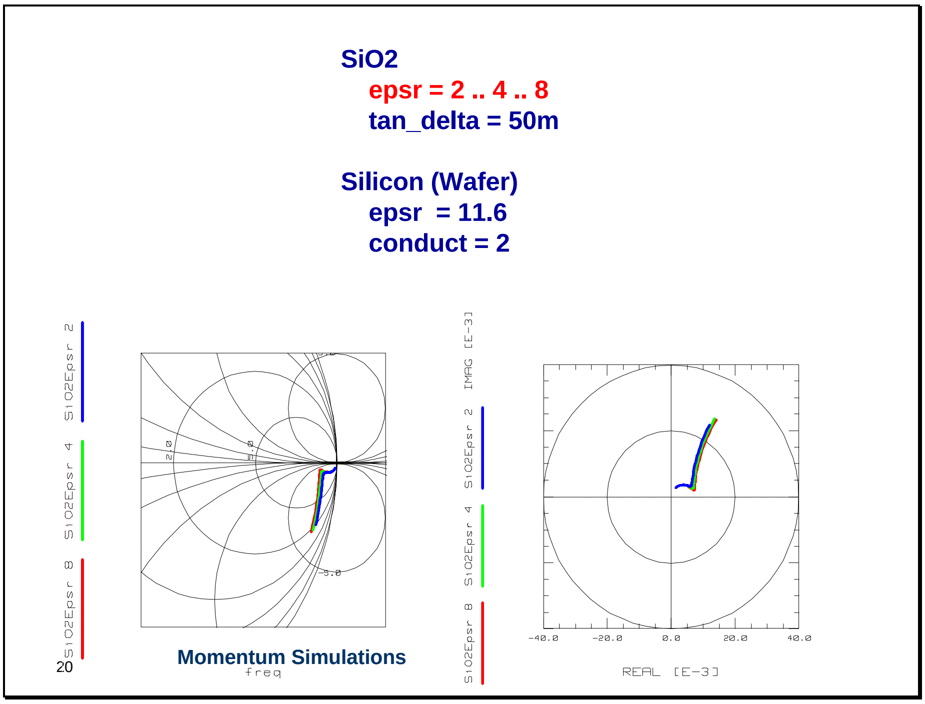
SiO2
epsr = 4
tan_delta = 50m

Silicon (Wafer)
epsr = 5 .. 11.6 .. 20
conduct = 2

Momentum Simulations

The silicon wafer epsilon is responsible for the phase shift after the knee.

Slide 20



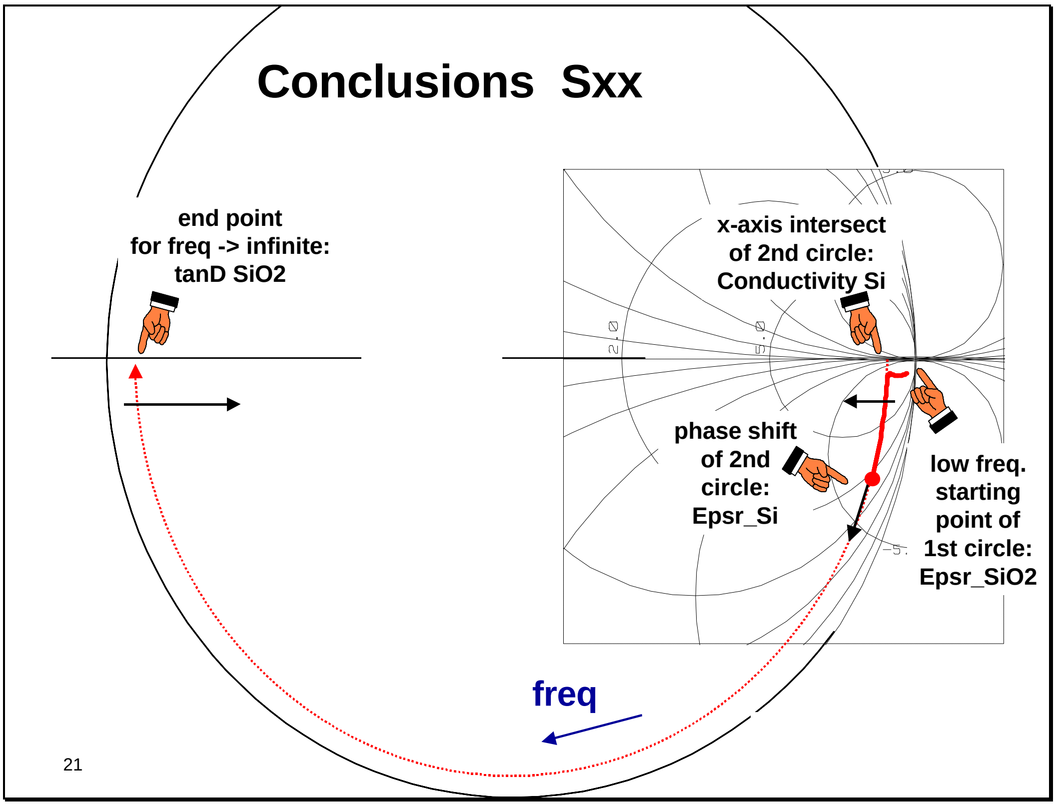
SiO2
epsr = 2 .. 4 .. 8
tan_delta = 50m

Silicon (Wafer)
epsr = 11.6
conduct = 2

Momentum Simulations

The SiO2 epsilon is responsible for the phase shift at low frequencies, below the knee.
Note: If there is no knee visible, both capacitors are in series and the smaller of them becomes the dominant one: the eps-r of the silicon wafer.

Slide 21



Conclusions Sxx

end point
for freq -> infinite:
tanD SiO2

x-axis intersect
of 2nd circle:
Conductivity Si

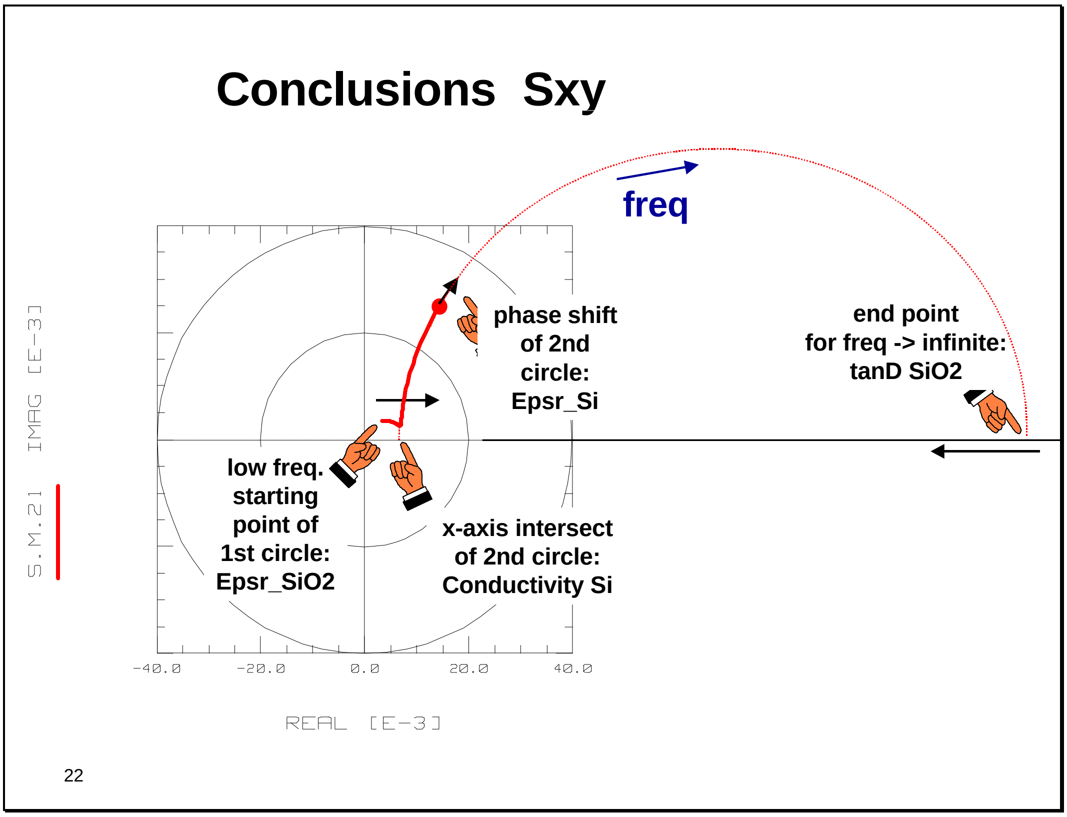
phase shift
of 2nd
circle:
Epsr_Si

low freq.
starting
point of
1st circle:
Epsr_SiO2

freq

This slide wraps-up the results from before.

Slide 22



Conclusions Sxy

freq

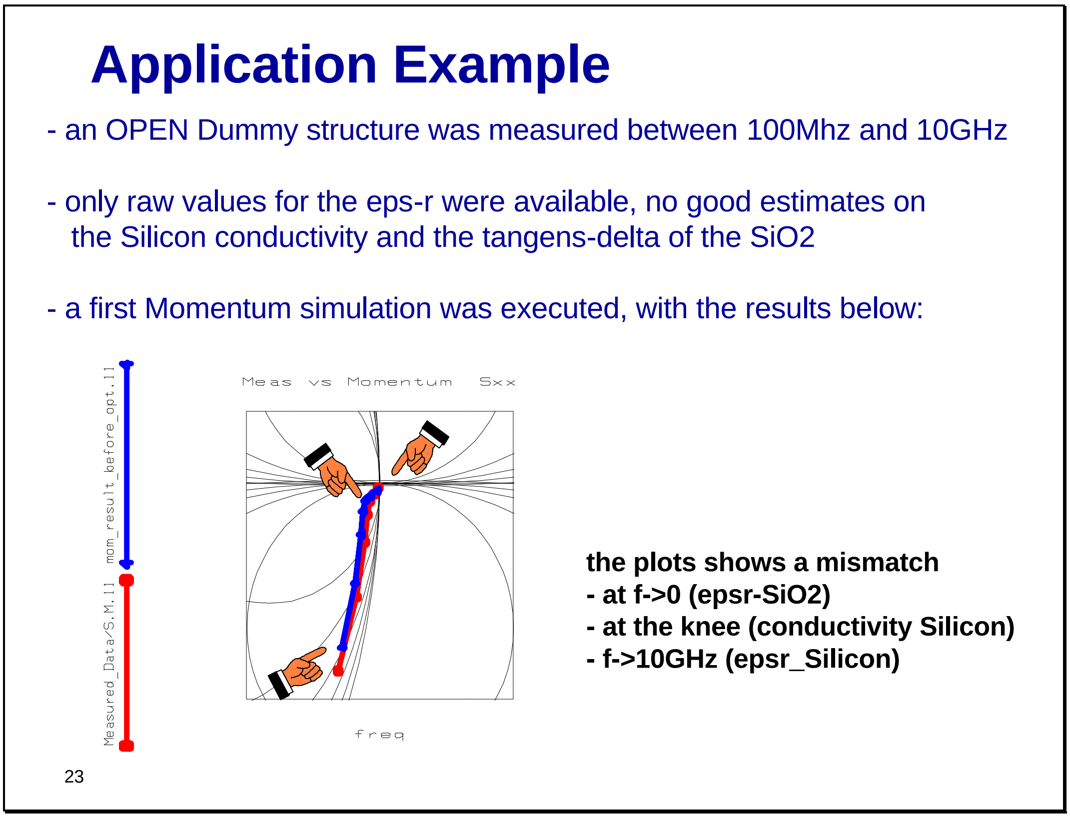
phase shift
of 2nd
circle:
Epsr_Si

end point
for freq -> infinite:
tanD SiO2

low freq.
starting
point of
1st circle:
Epsr_SiO2

x-axis intersect
of 2nd circle:
Conductivity Si

Slide 23



Application Example

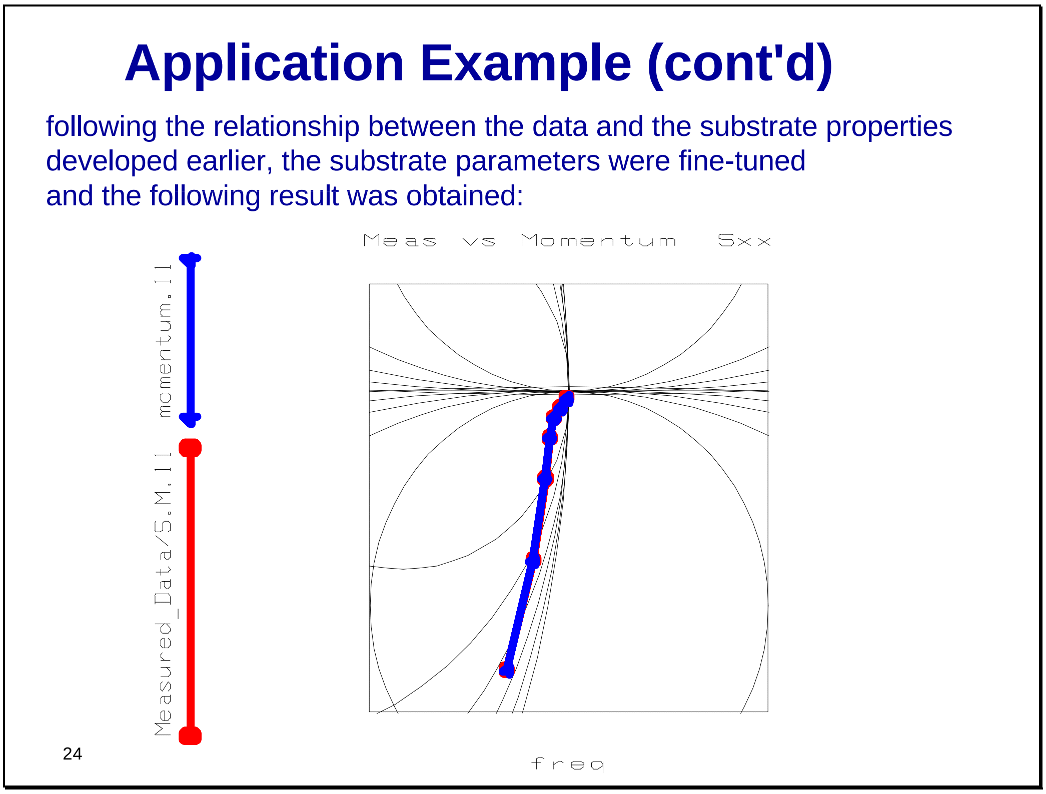
- an OPEN Dummy structure was measured between 100Mhz and 10GHz

- only raw values for the eps-r were available, no good estimates on the Silicon conductivity and the tangens-delta of the SiO2

- a first Momentum simulation was executed, with the results below:

the plots shows a mismatch
- at f->0 (epsr-SiO2)
- at the knee (conductivity Silicon)
- f->10GHz (epsr_Silicon)

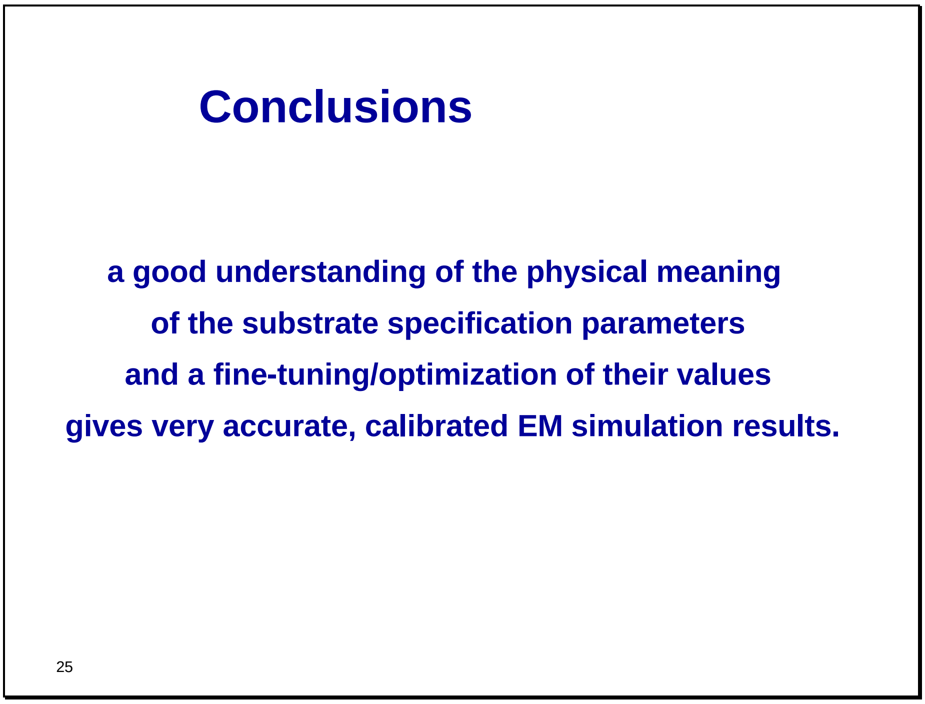
Slide 24



Application Example (cont'd)

following the relationship between the data and the substrate properties developed earlier, the substrate parameters were fine-tuned and the following result was obtained:

Slide 25



Conclusions

a good understanding of the physical meaning
of the substrate specification parameters
and a fine-tuning/optimization of their values
gives very accurate, calibrated EM simulation results.

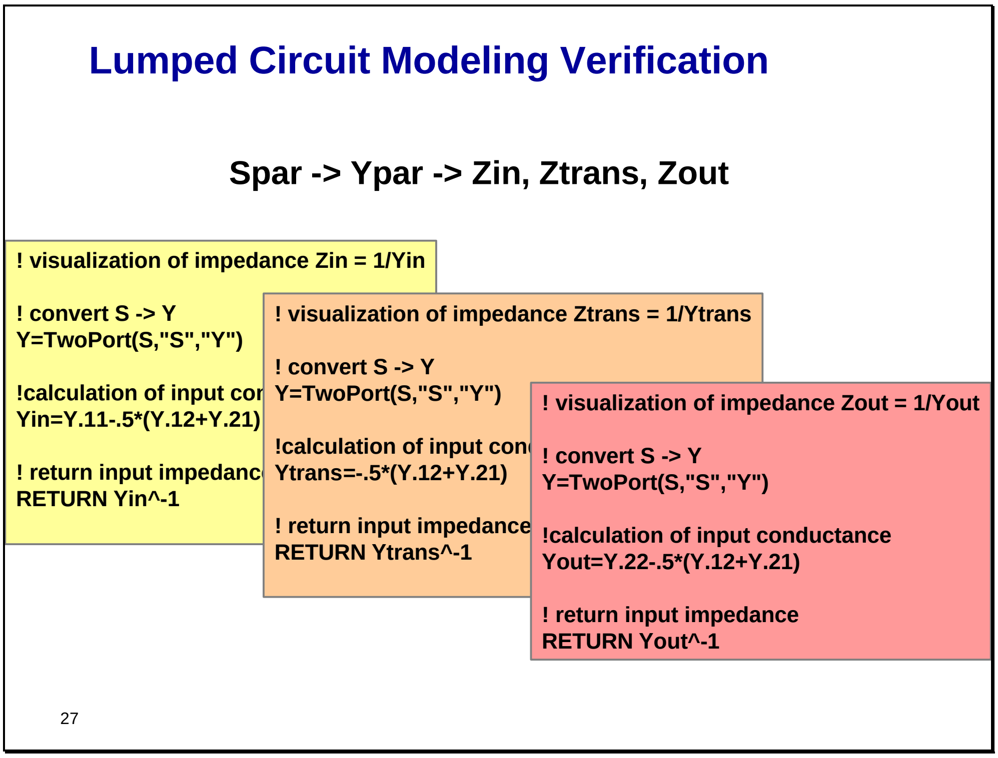
Slide 26

Appendix

lumped components modeling

as a side aspect, the Momentum simulation results were modeled with a lumped component schematic in ADS and the fitting was verified. The following slides depict the result.

Slide 27



Lumped Circuit Modeling Verification

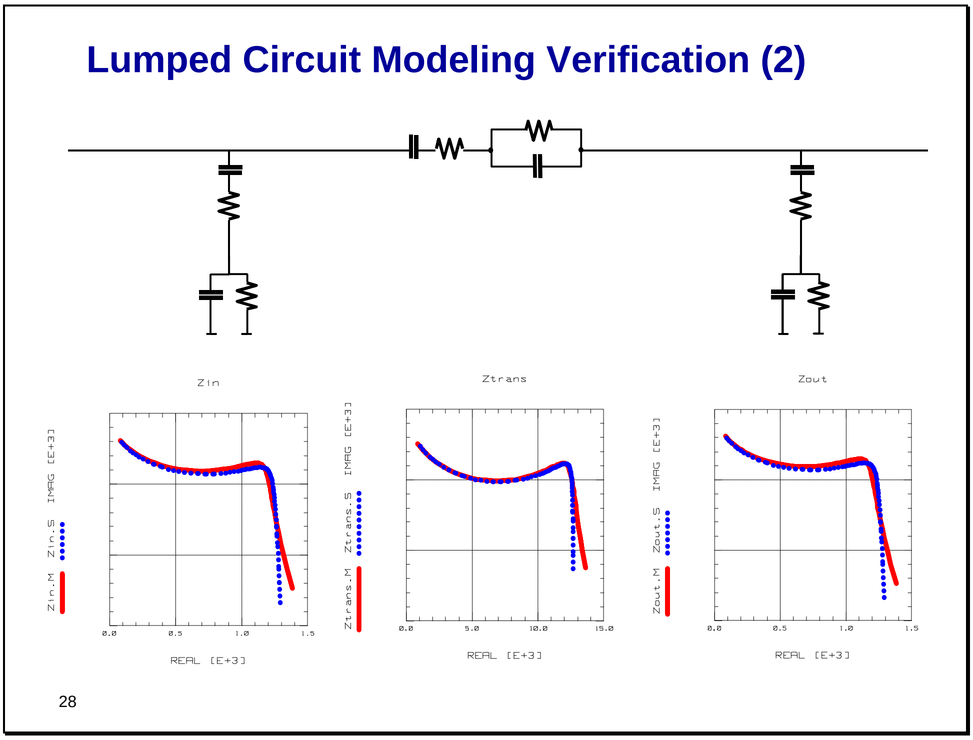
Spar -> Ypar -> Zin, Ztrans, Zout

```
! visualization of impedance Zin = 1/Yin

! convert S -> Y
Y=TwoPort(S,"S","Y")

!calculation of input cor
Yin=Y.11-.5*(Y.12+Y.21)

! return input impedanc
RETURN Yin^-1
```

```
! visualization of impedance Ztrans = 1/Ytrans

! convert S -> Y
Y=TwoPort(S,"S","Y")

!calculation of input con
Ytrans=-.5*(Y.12+Y.21)

! return input impedance
RETURN Ytrans^-1
```

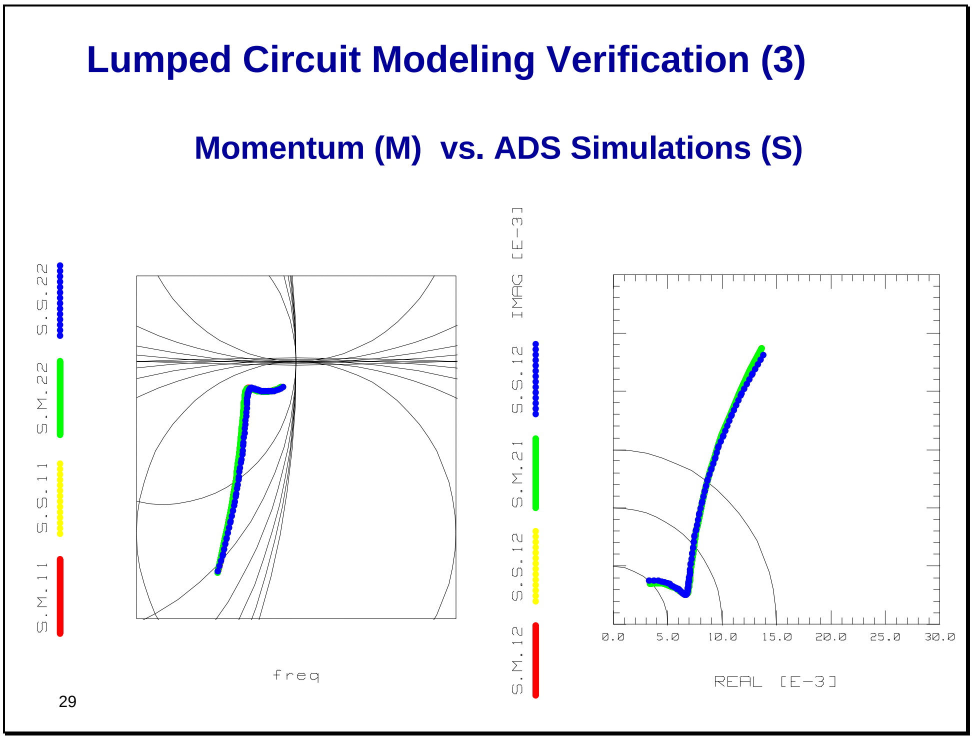
```
! visualization of impedance Zout = 1/Yout

! convert S -> Y
Y=TwoPort(S,"S","Y")

!calculation of input conductance
Yout=Y.22-.5*(Y.12+Y.21)

! return input impedance
RETURN Yout^-1
```

Slide 28



Lumped Circuit Modeling Verification (2)

Slide 29



Lumped Circuit Modeling Verification (3)

Momentum (M) vs. ADS Simulations (S)