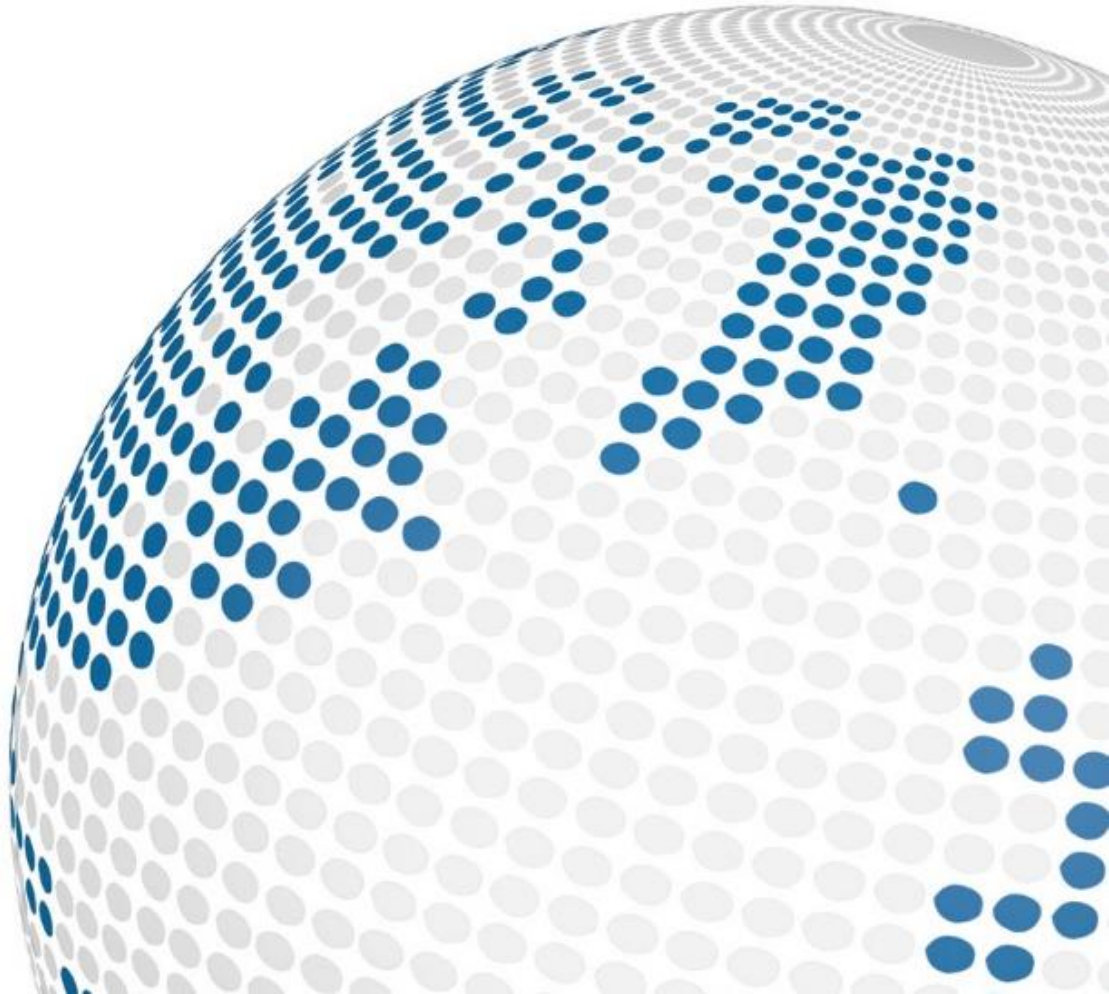
TSV Modeling from kHz to RF

32nd AKB workshop, Crolles, France

Kund Molnár

14.11.2019

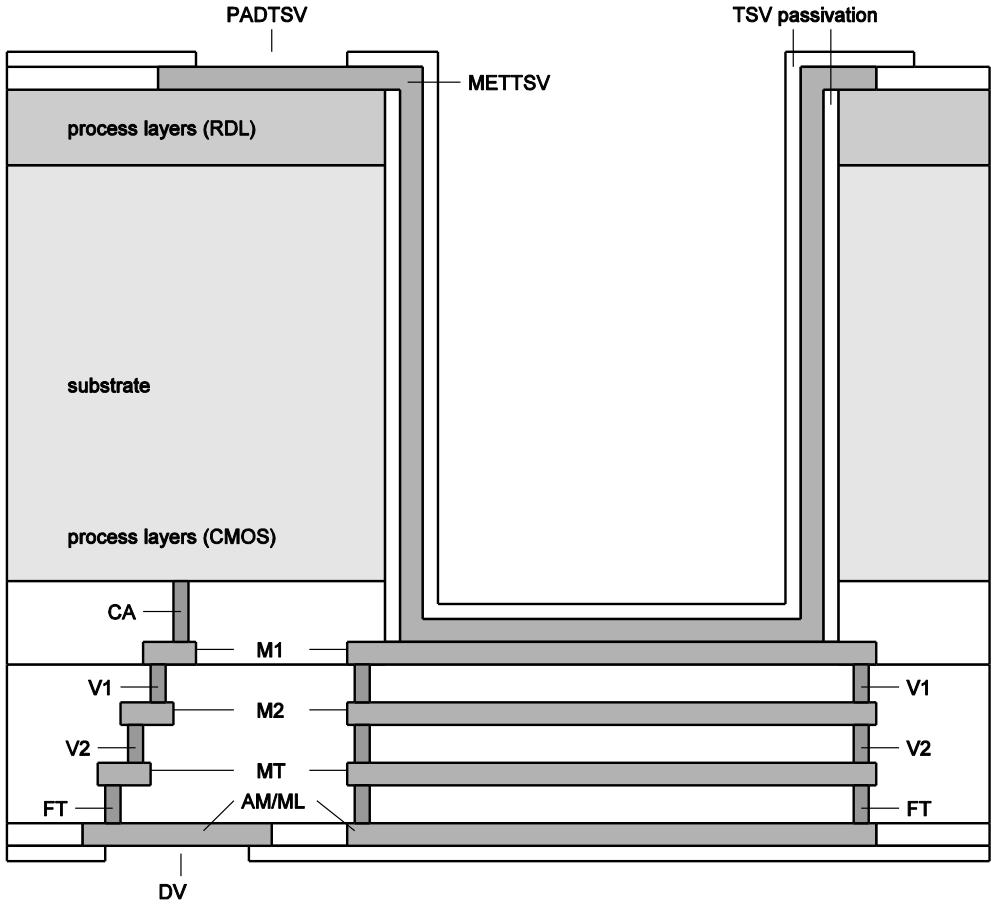


TSV Technology

TSV Modeling

- **3D VLSI technology** integrates heterogeneous functions (logic, memory, MEMS, RF, analog/digital, sensors).
- Paths of power delivery and high-frequency signals between building blocks needed.
- **Bond wire replacement**: long wires have large inductance and resistance: power consumption, signal integrity and propagation requirements are not fulfilled.
- **Through Silicon Via (TSV)** is the new key element joining the stacked circuits. They serve as **interconnects** between the two sides of a silicon wafer.

- **TSV properties are determined by:**
  - Occupied area
  - Low TSV resistance
  - Conductance of the silicon substrate
  - Thin silicon dioxide insulator



TSV Characterization

TSV Modeling

Test Structures:

S-parameter structures of 40µm and 80µm TSVs

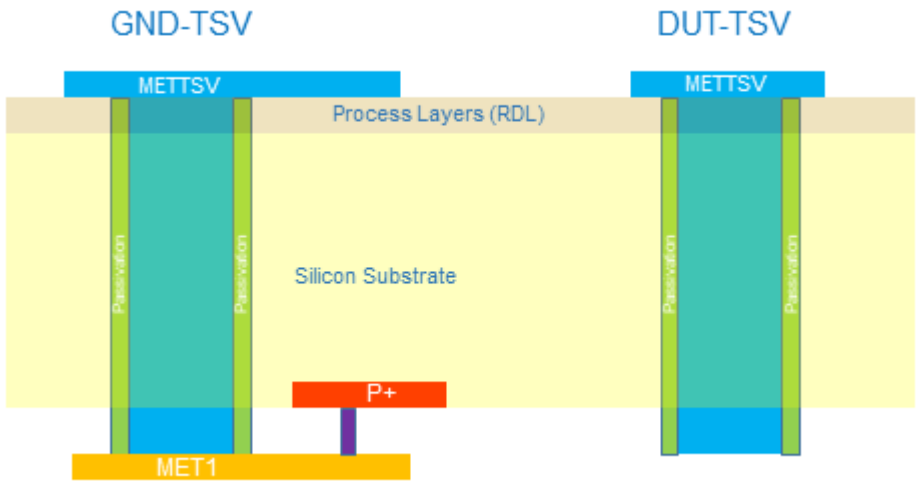
Joint usage of two measurement domains:

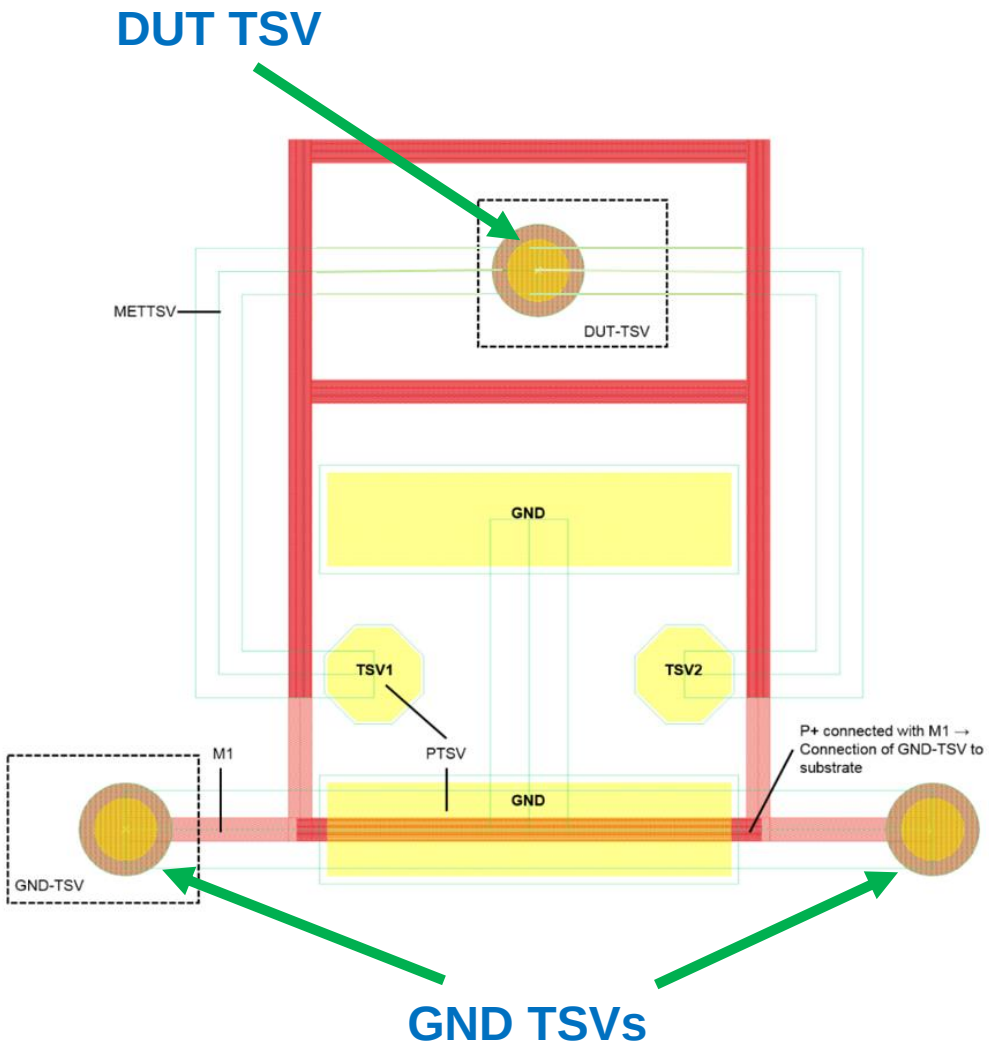
LCR meter measurement:

admittance (Y) measured **(**1 kHz – 1 MHz)

RF measurement:

S-parameters measured (100MHz – 40GHz)

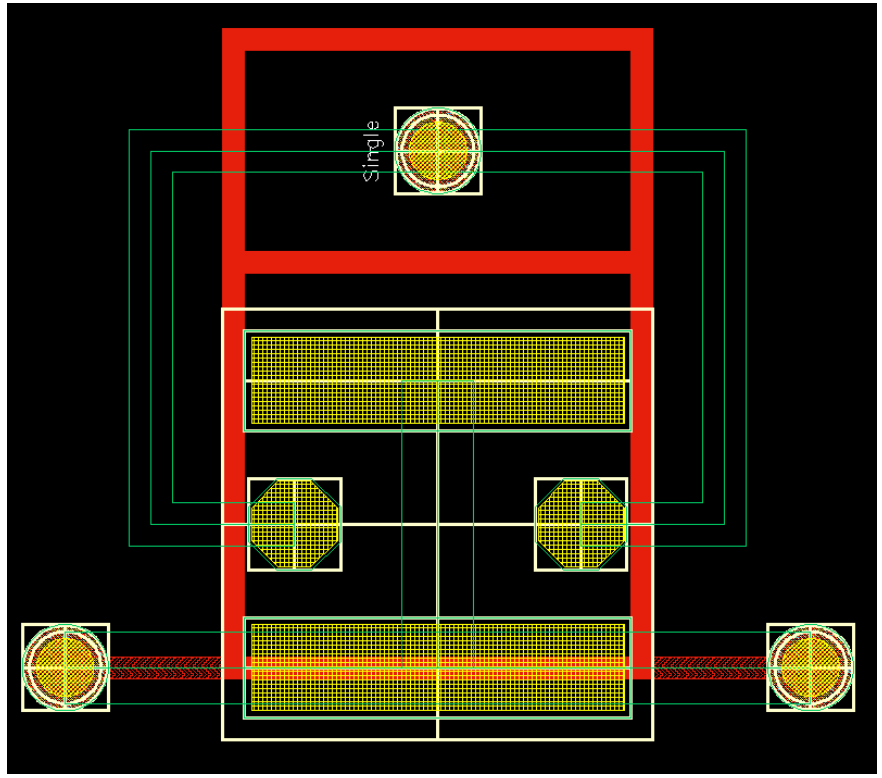


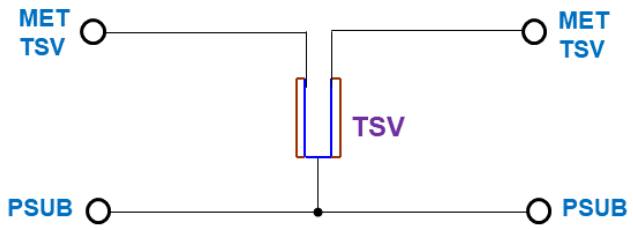


TSV Test Structures for Model Extraction

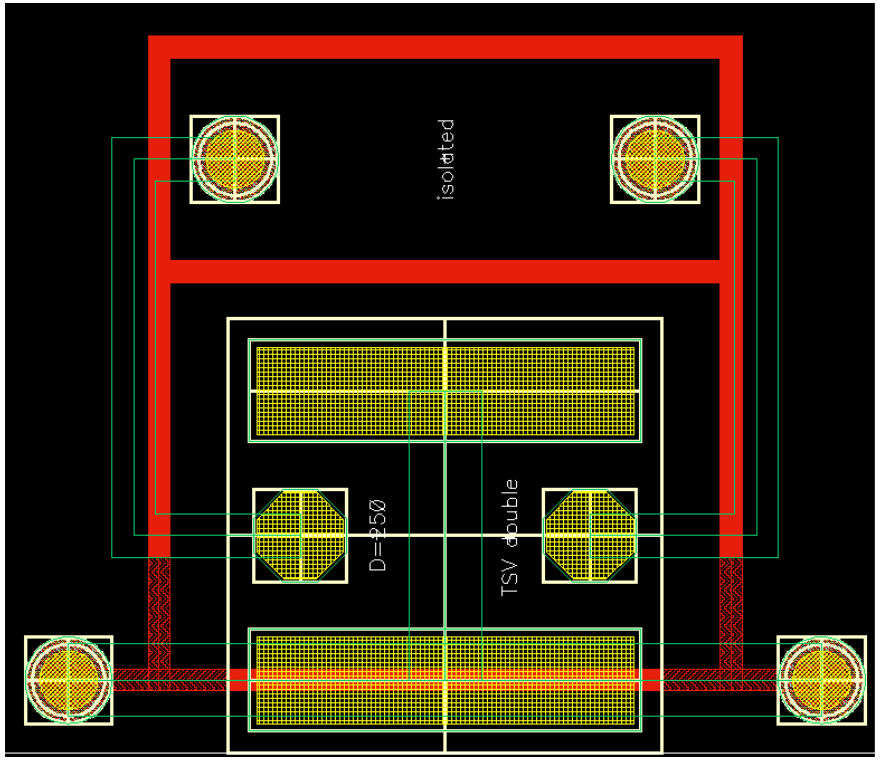
TSV Modeling

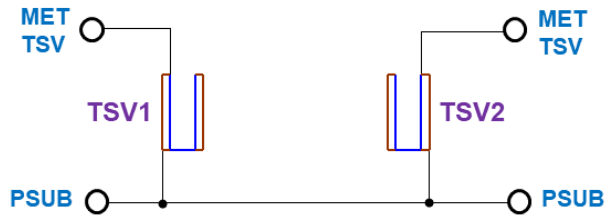
Single TSV





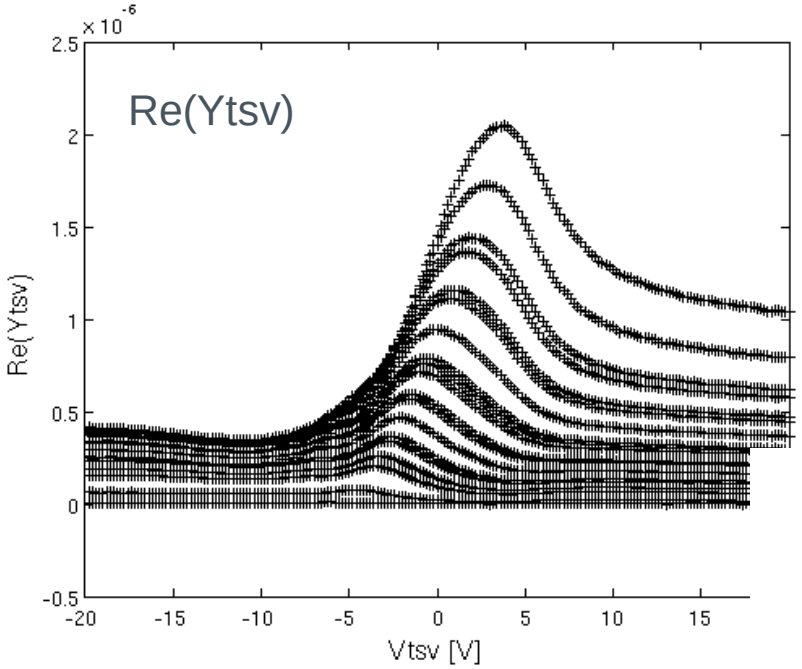
Isolated TSVs

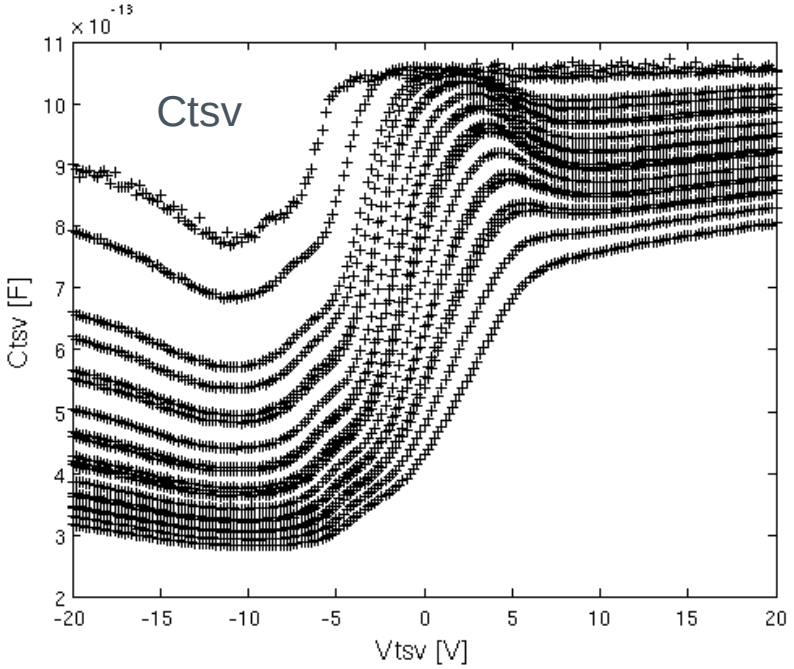


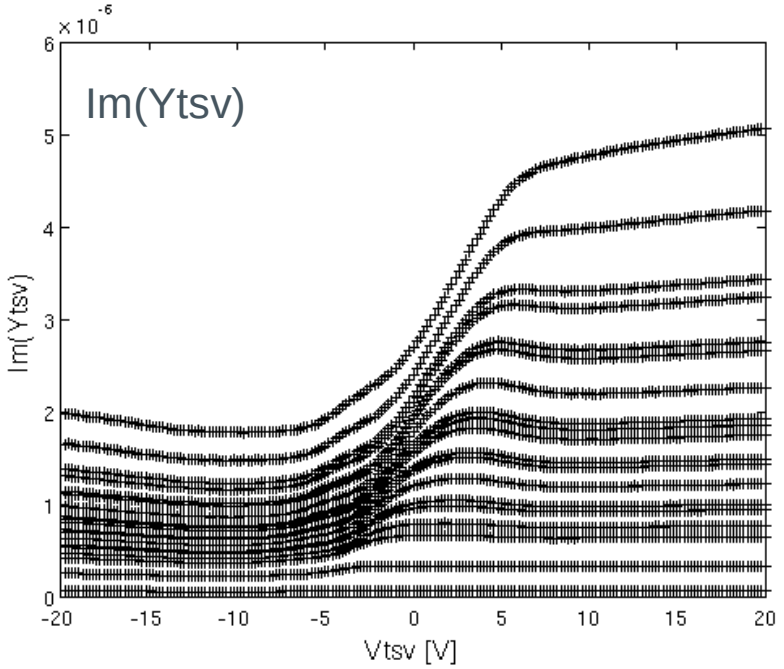


LCR Measurement

TSV40 Modeling







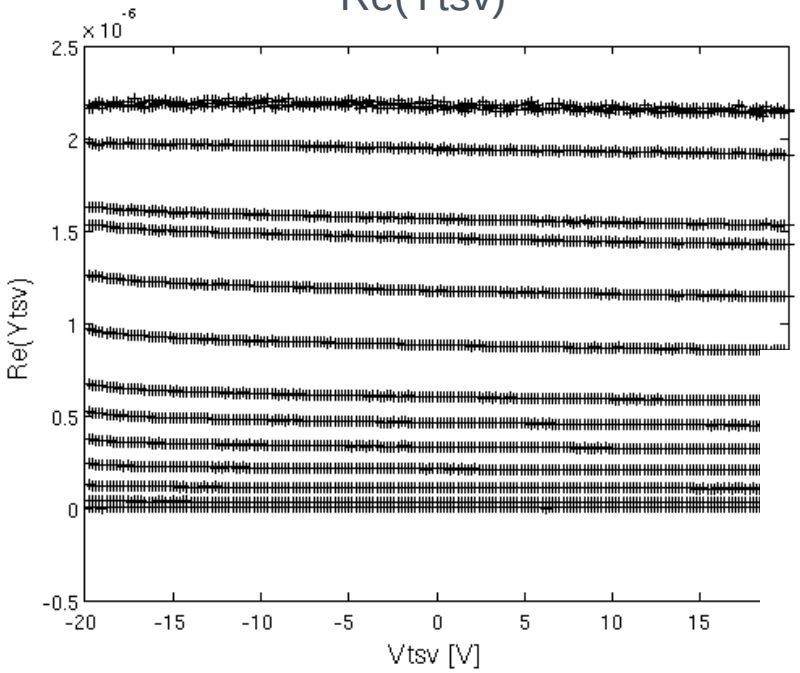
f=10 kHz – 1MHz

Ytsv=Yme-Yo

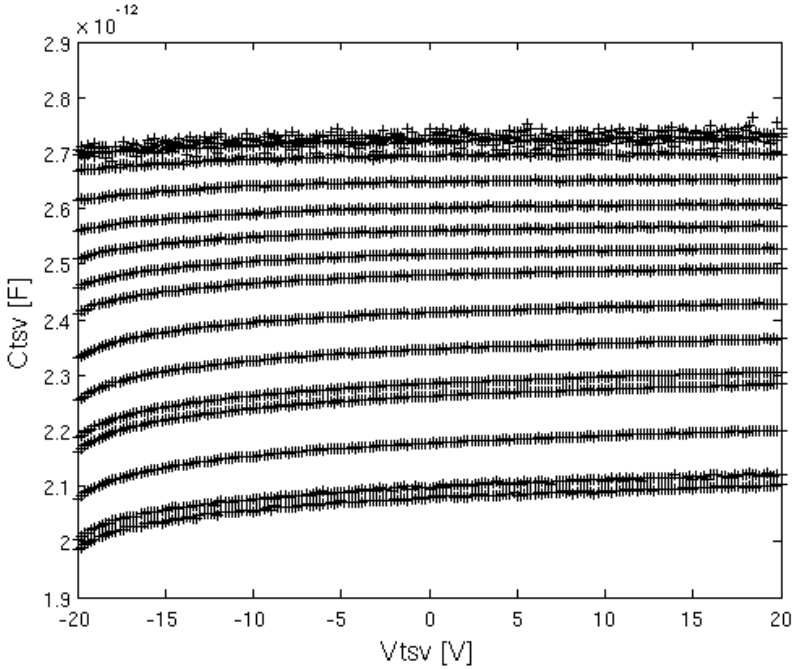
LCR Measurement

TSV80 Modeling

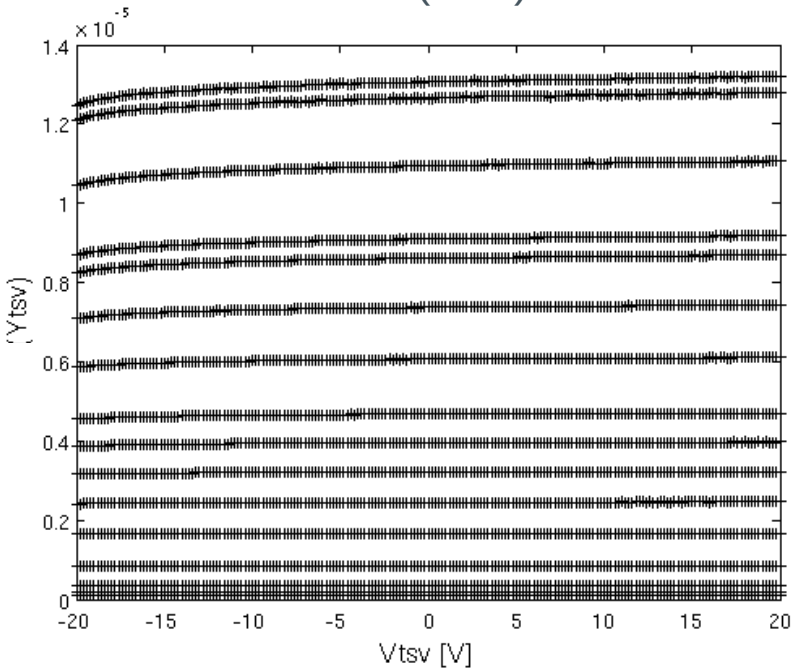
Re(Ytsv)



Ctsv



Im(Ytsv)

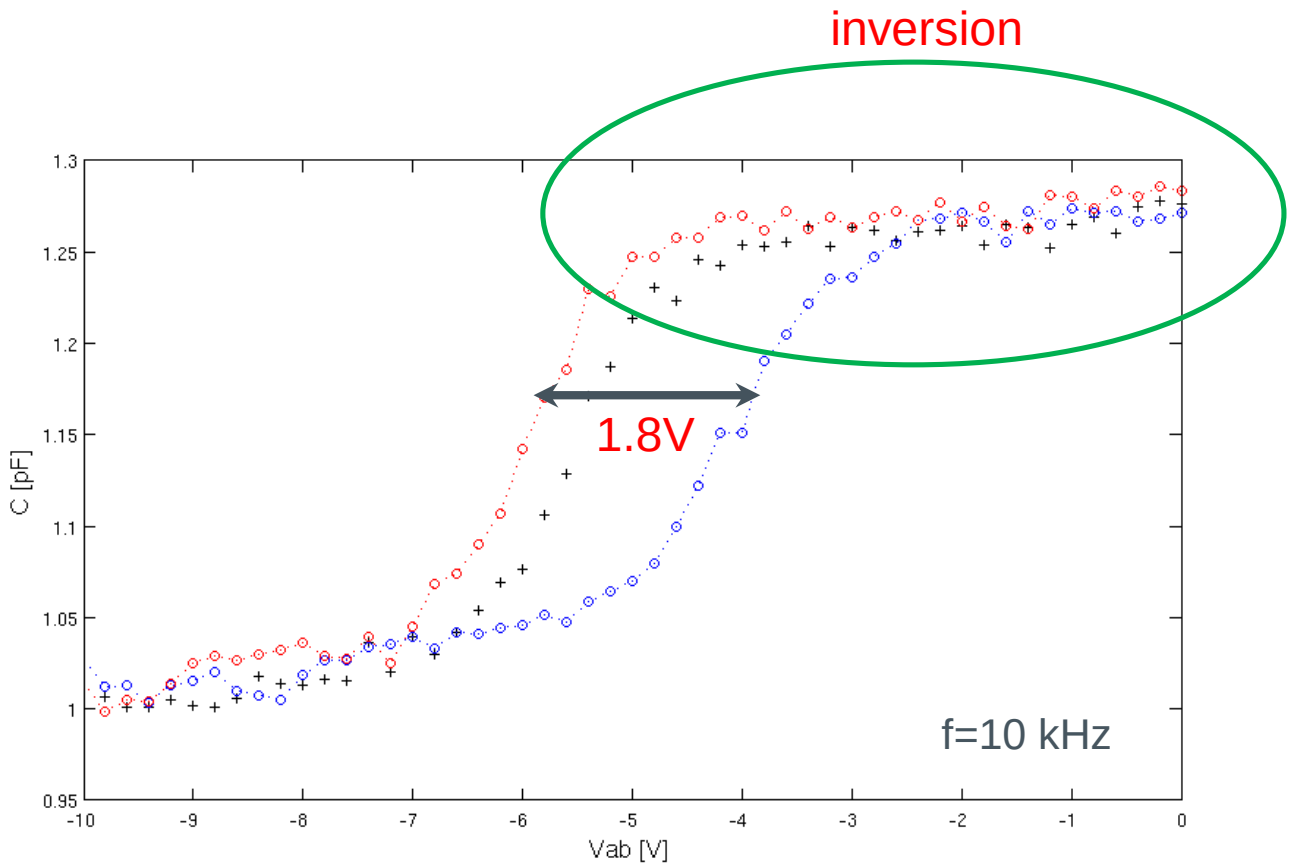


f=10 kHz – 1MHz

Ytsv=Yme-Yo

High Temperature Biasing

TSV40 Modeling



Mobile positive charges can be moved away (-5V) or pushed to the SiO2/p-sub interface (5V)

The experiment proves the existence of a pre-inverted surface.

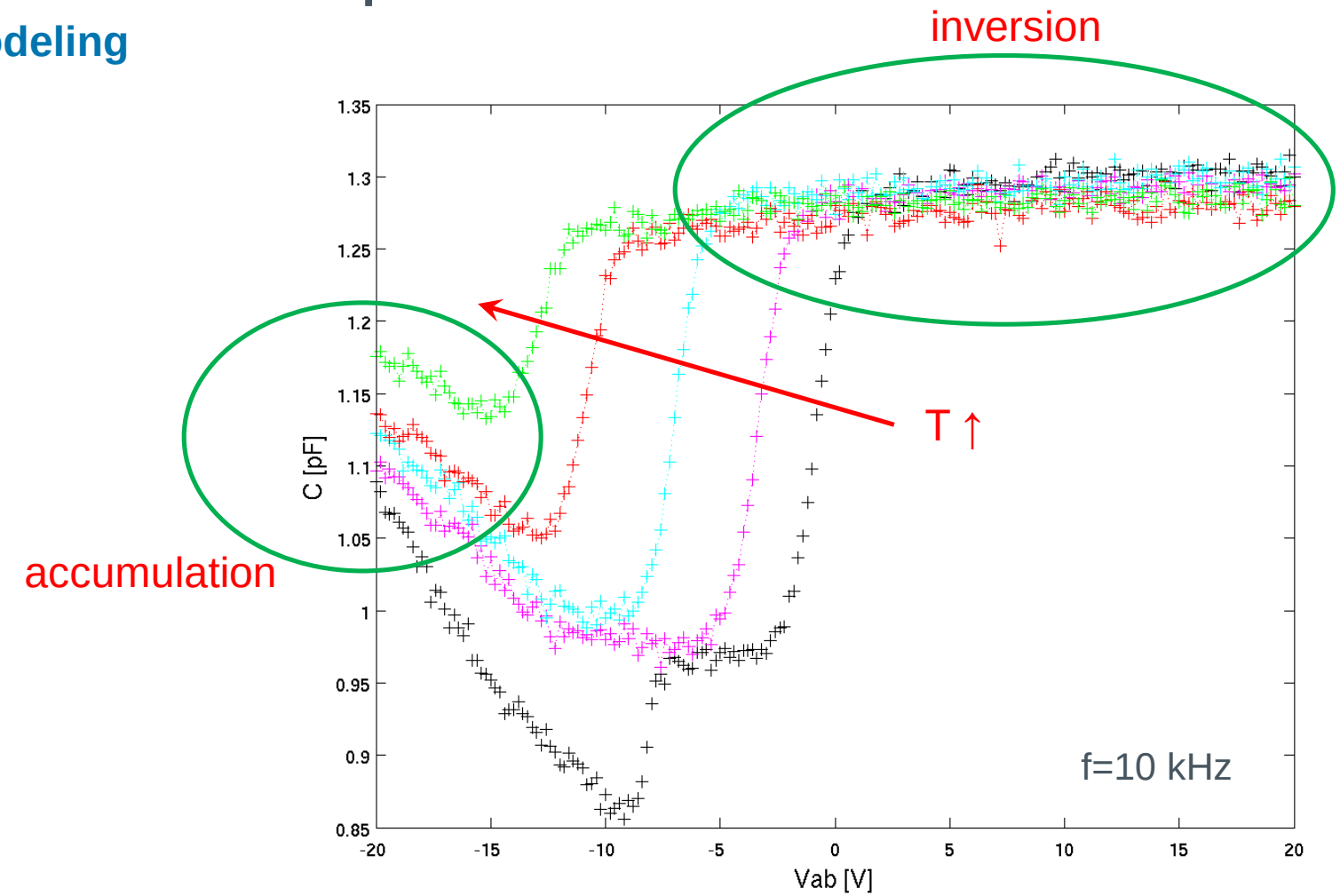
Black curve: original status, measured at 25C.

Blue curve: -5V bias applied for 30min at 125C, measured at 25C.

Red curve: +5V bias applied for 30min at 125C, measured at 25C.

Temperature Dependence

TSV40 Modeling



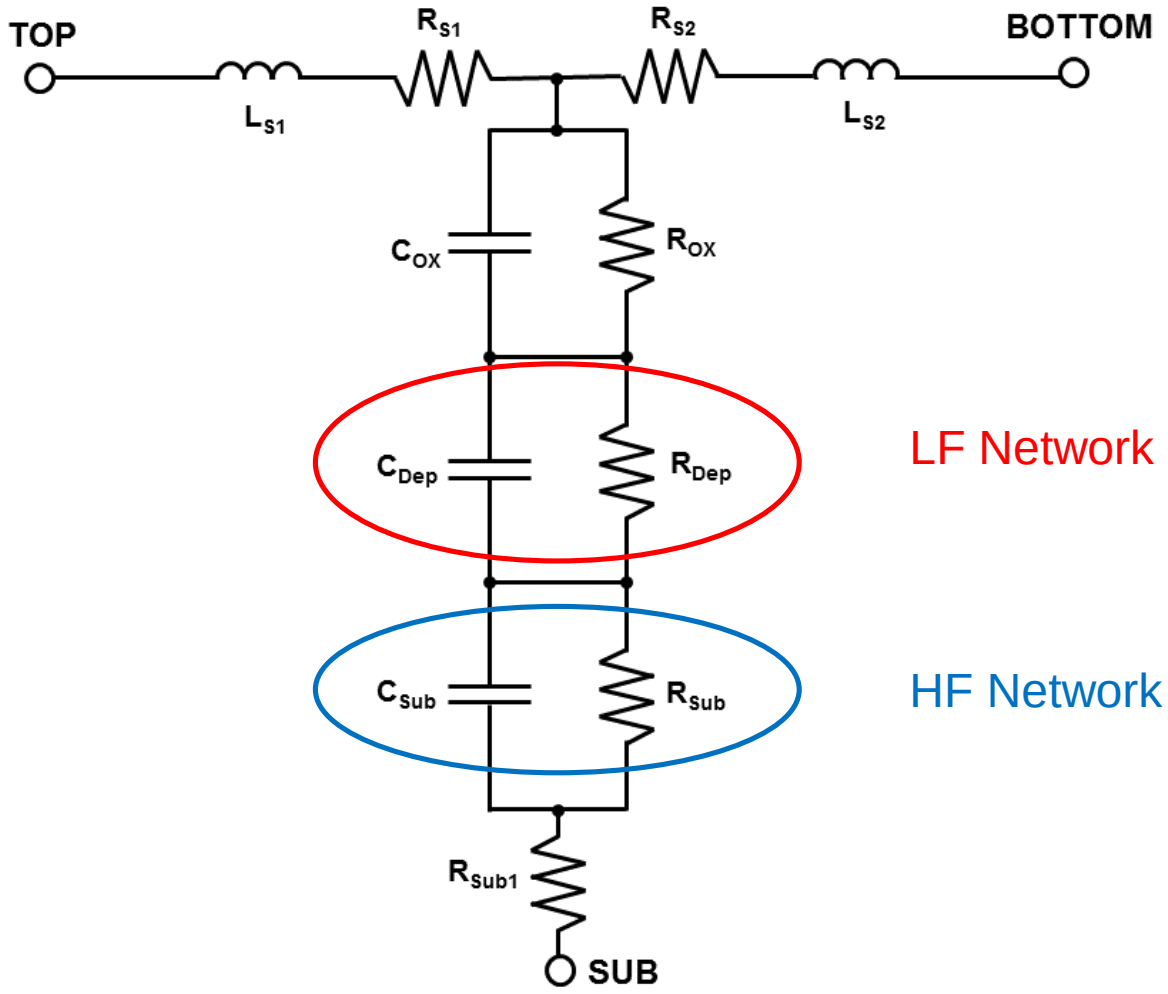
T=-40C, 0C, 25C, 75C, 100C

Inversion is more and more present at higher temperatures.

TSV Subcircuit

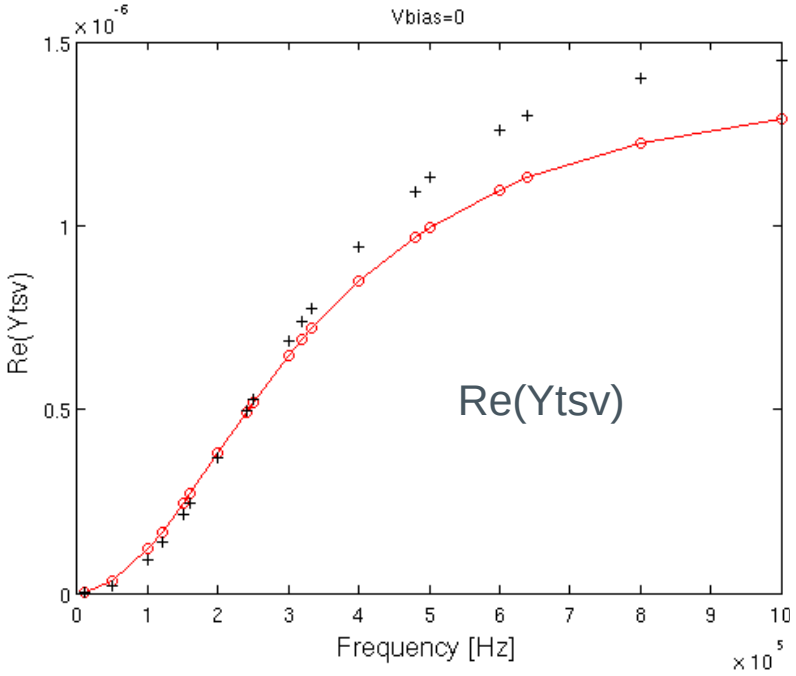
TSV Modeling

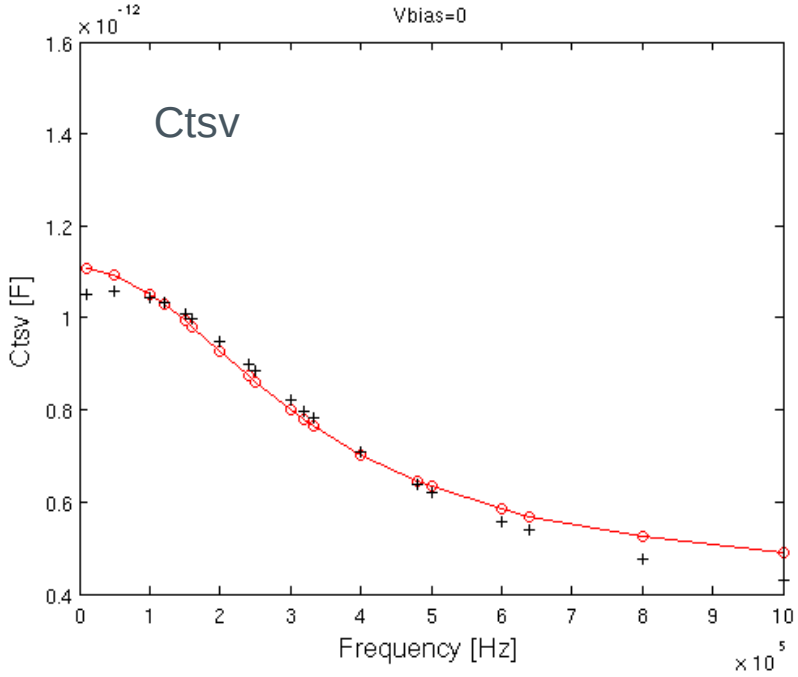
$R_{s1/2}$	Series resistances
$L_{s1/2}$	Series inductances
C_{ox}	METTSV to PSUB capacitance
R_{ox}	METTSV to PSUB conductance
C_{dep}	Depletion capacitance
R_{dep}	Resistance of the depletion layer
C_{sub}	Substrate capacitance
R_{sub}	Substrate resistance
R_{sub1}	Substrate resistance

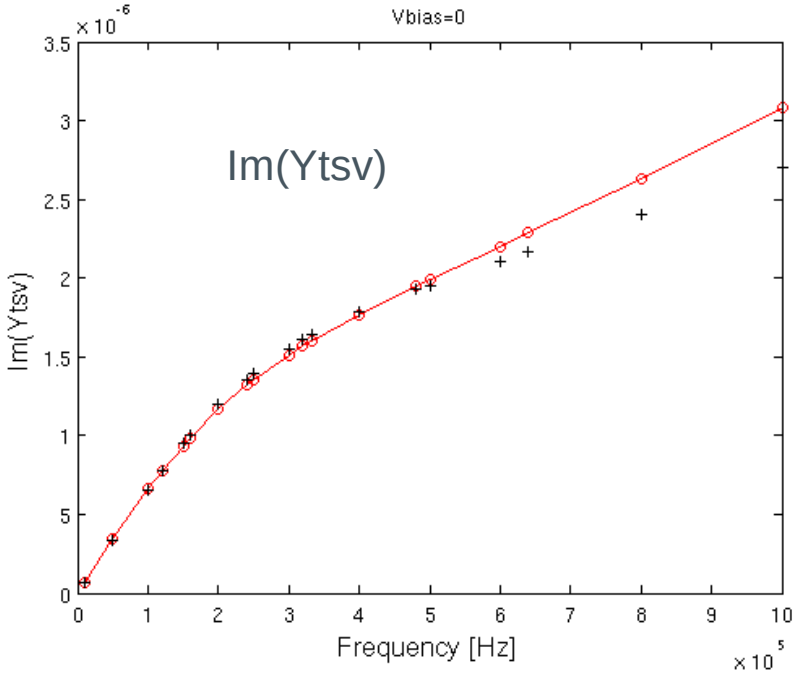


Isolated TSV: LCR Extraction at V=0

TSV40 Modeling



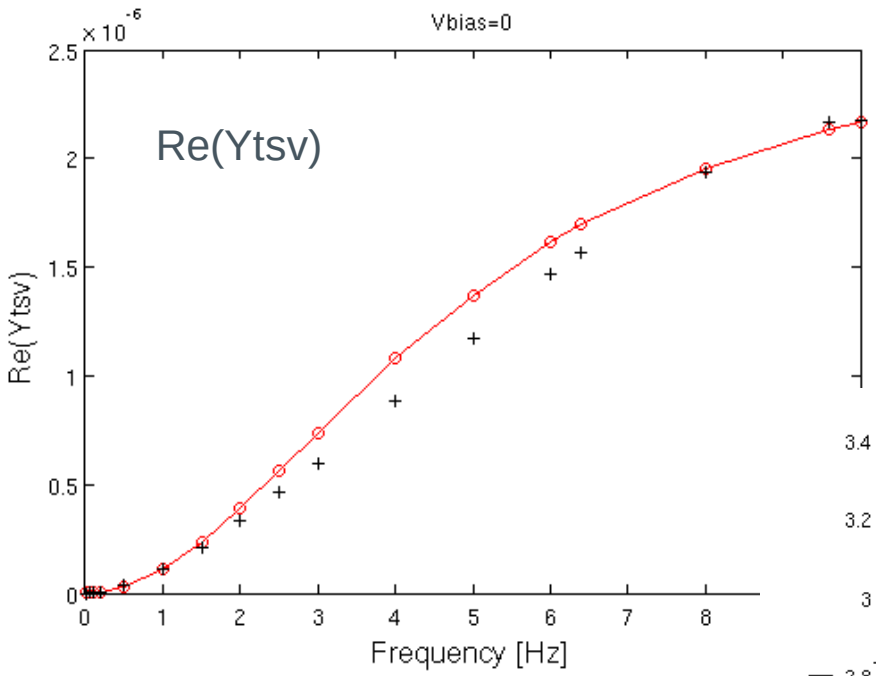


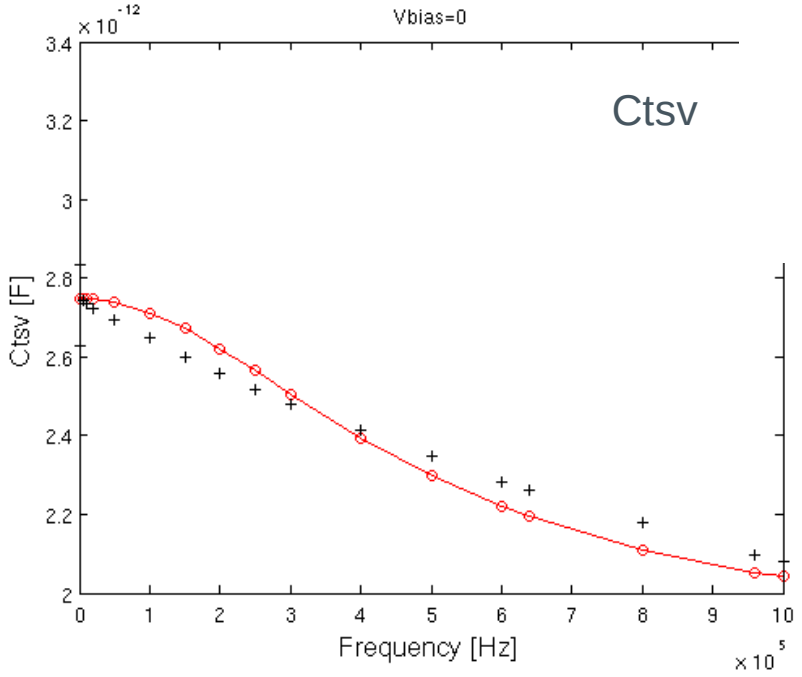


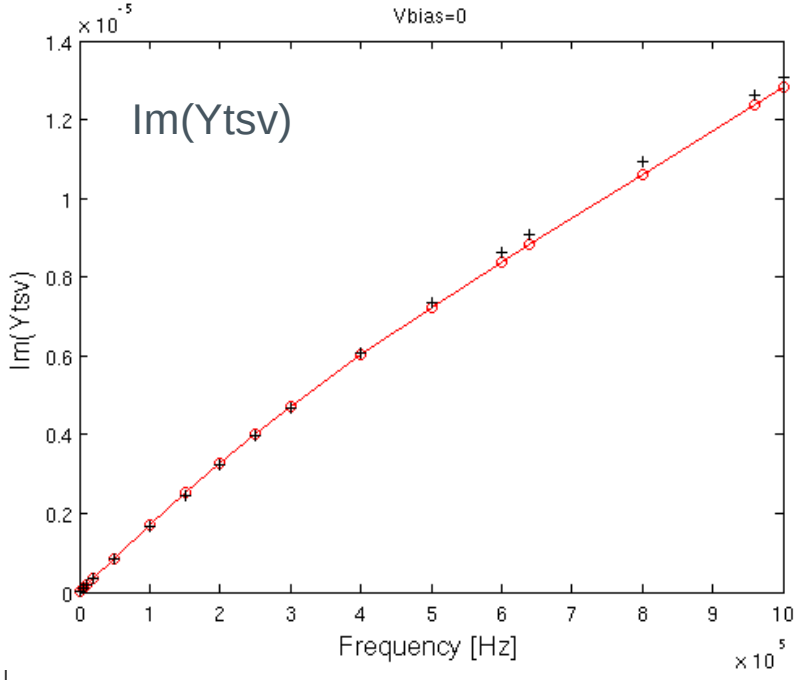
simulation (o) vs. measurement (+)

Isolated TSV: LCR Extraction at V=0

TSV80 Modeling



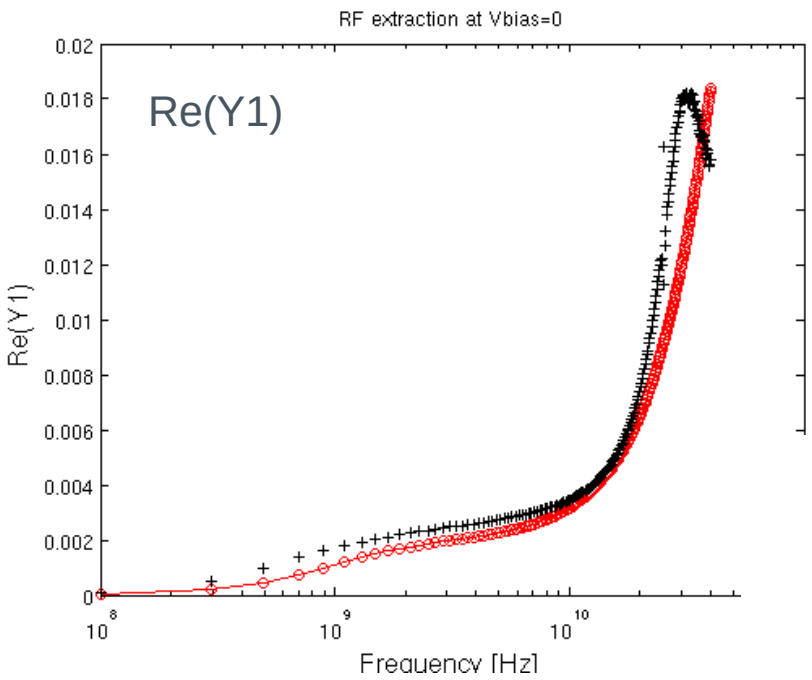


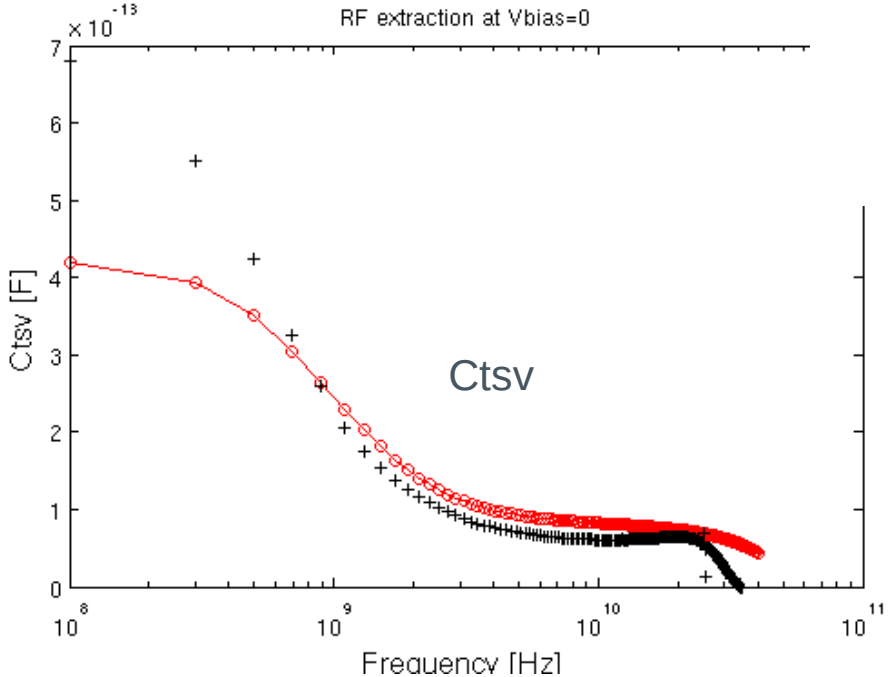


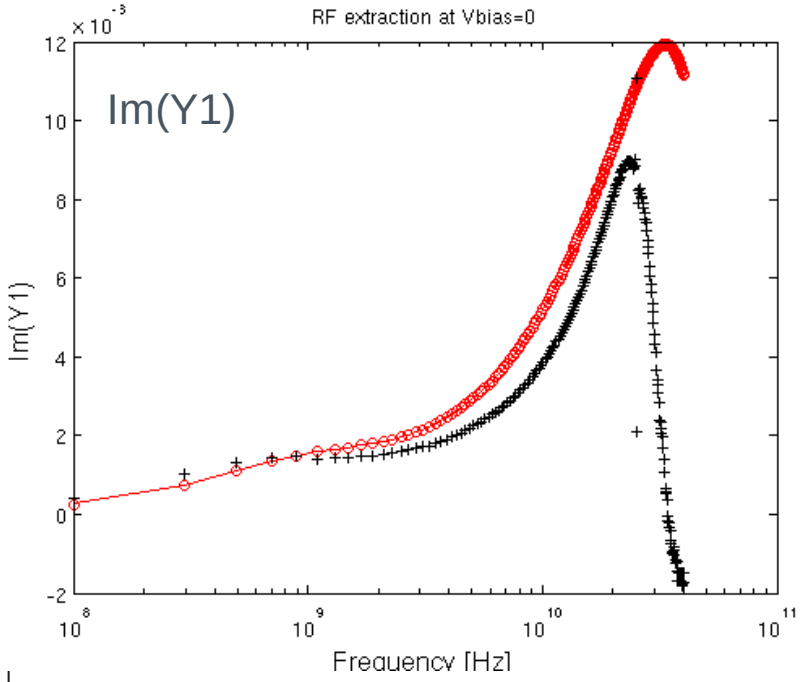
simulation (o) vs. measurement (+)

Isolated TSV: RF Input Admittance at V=0

TSV40 Modeling







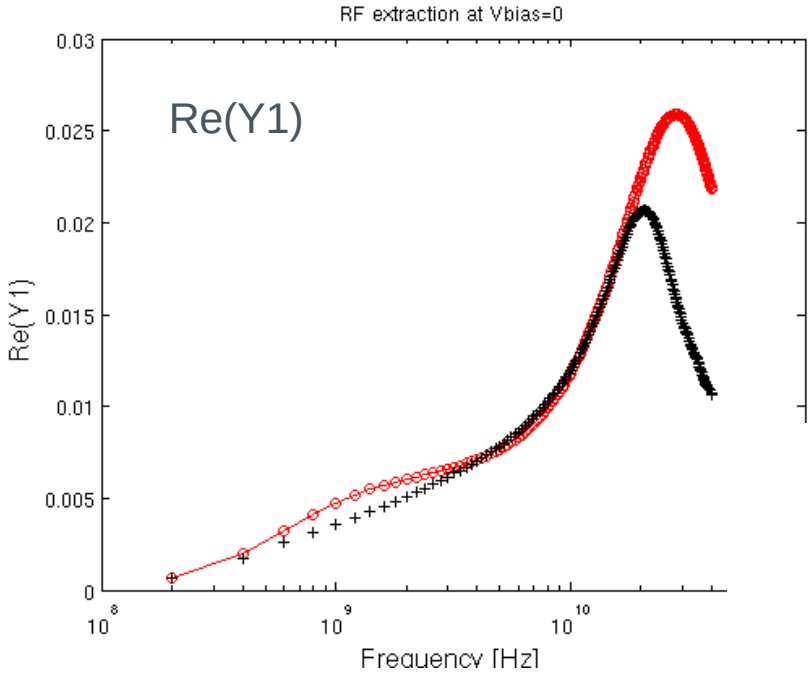
$Y_1 = Y_{11} + (Y_{12} + Y_{21})/2$

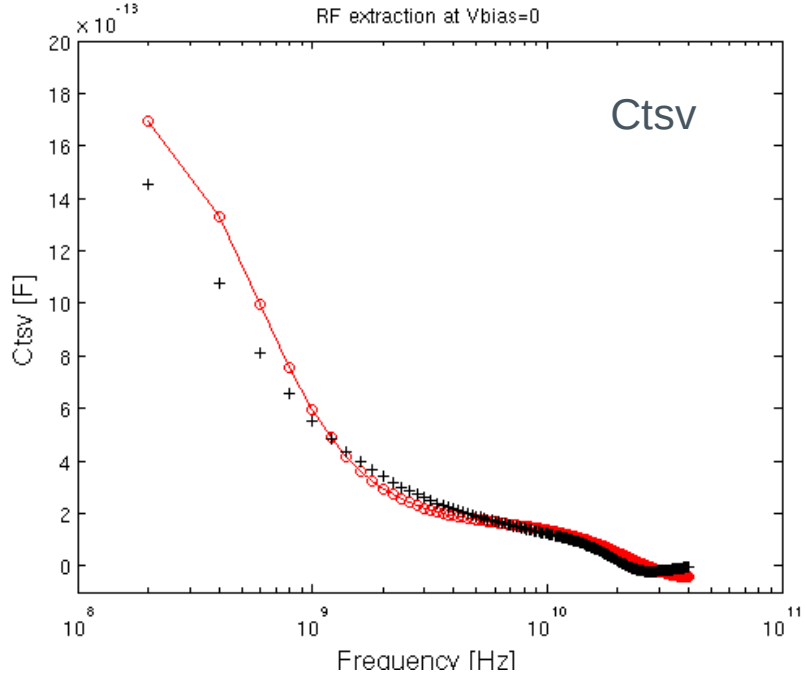
$C_{tsv} = Im(Y_1)/\omega$

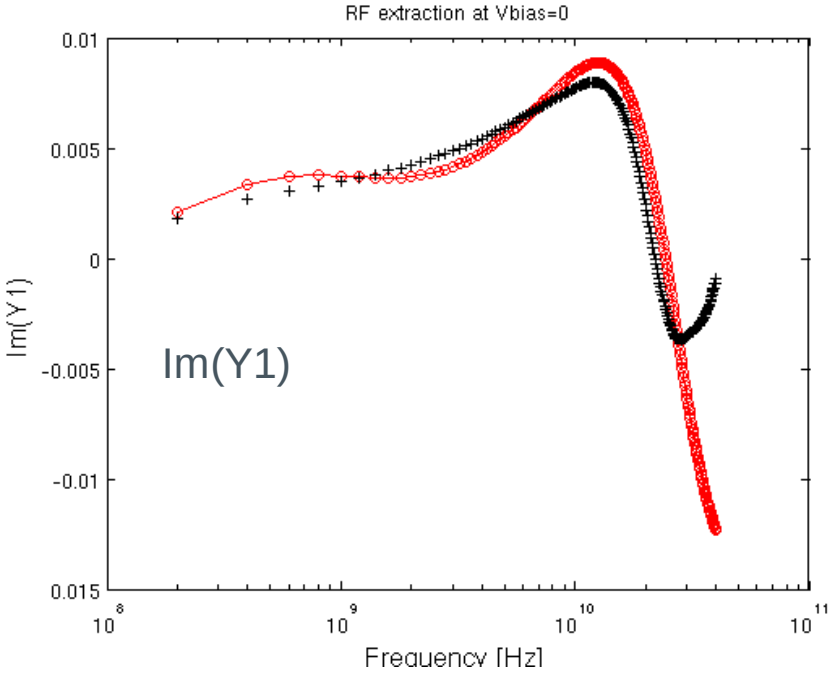
simulation (o) vs. measurement (+)

Isolated TSV: RF Input Admittance at V=0

TSV80 Modeling



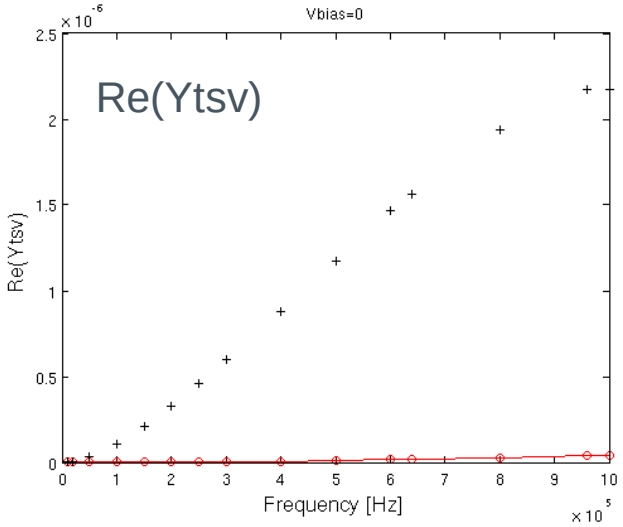


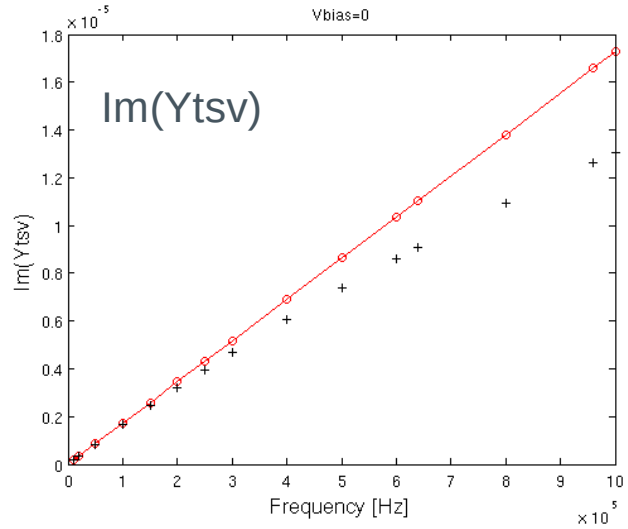


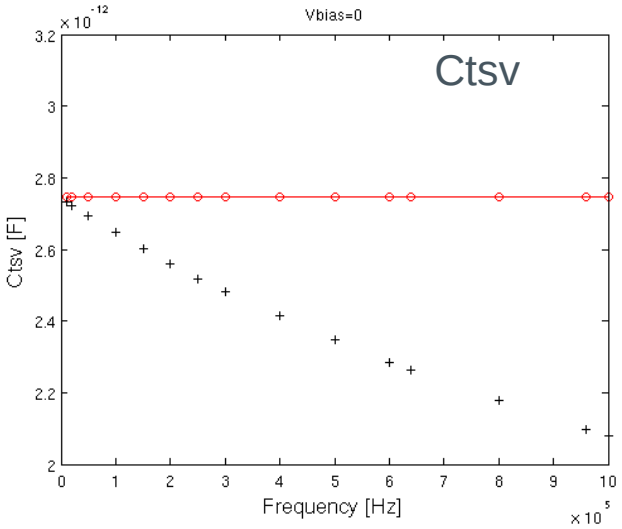
simulation (o) vs. measurement (+)

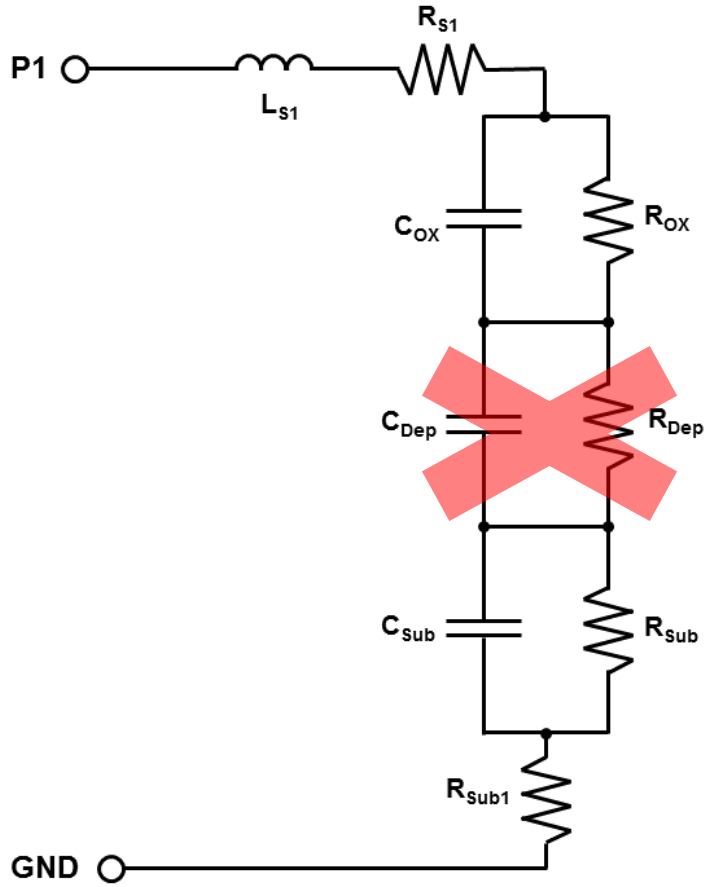
Isolated TSV: LF Network Omitted

TSV80 Modeling







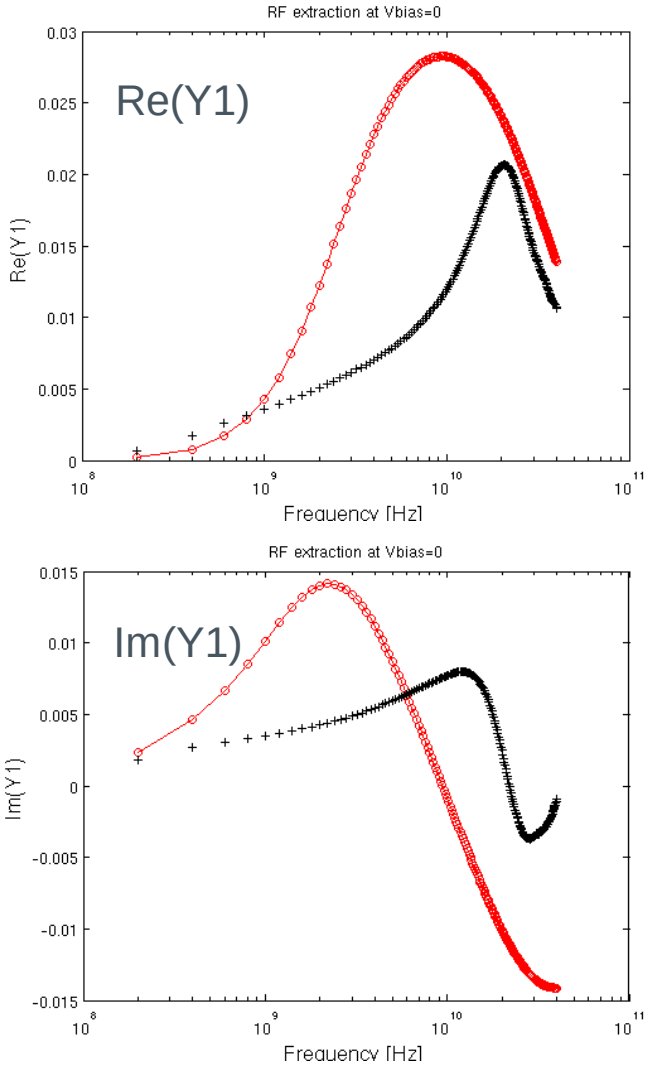


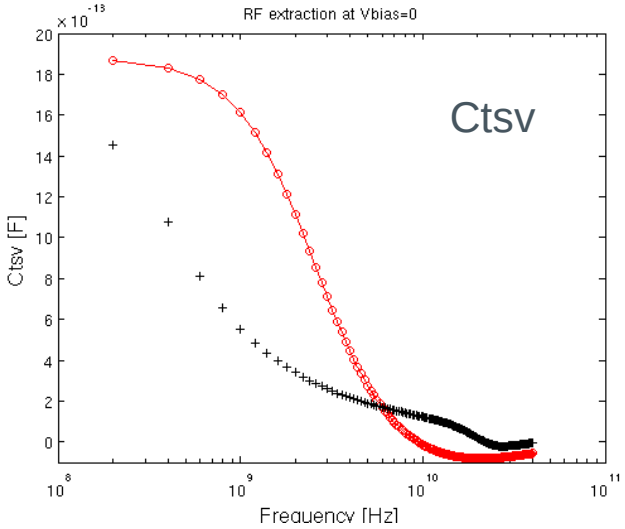
simulation (o) vs. measurement (+)

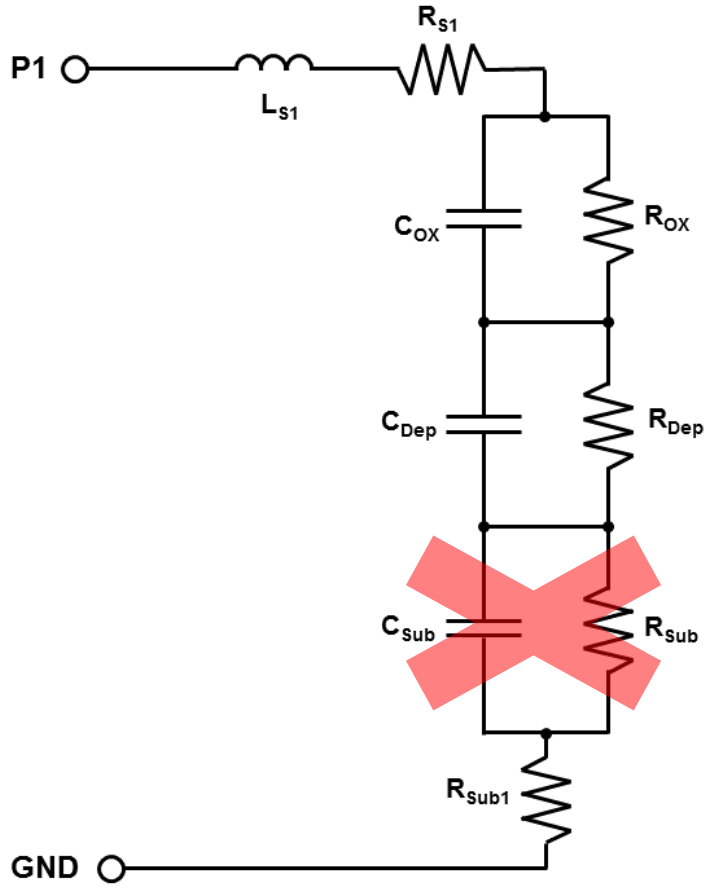
LF Pole deactivated. Result at f > 0.5 GHz nearly unchanged!

Isolated TSV: HF Network Omitted

TSV80 Modeling







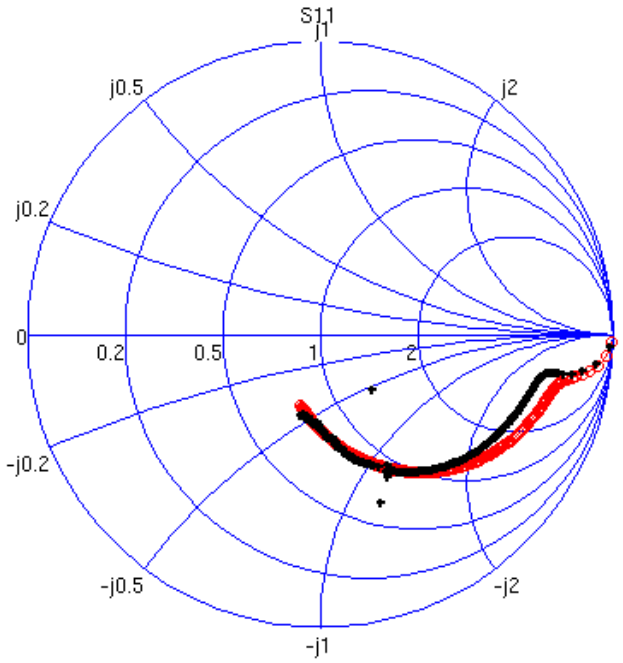
HF Pole deactivated. Result at f < 1 MHz unchanged!

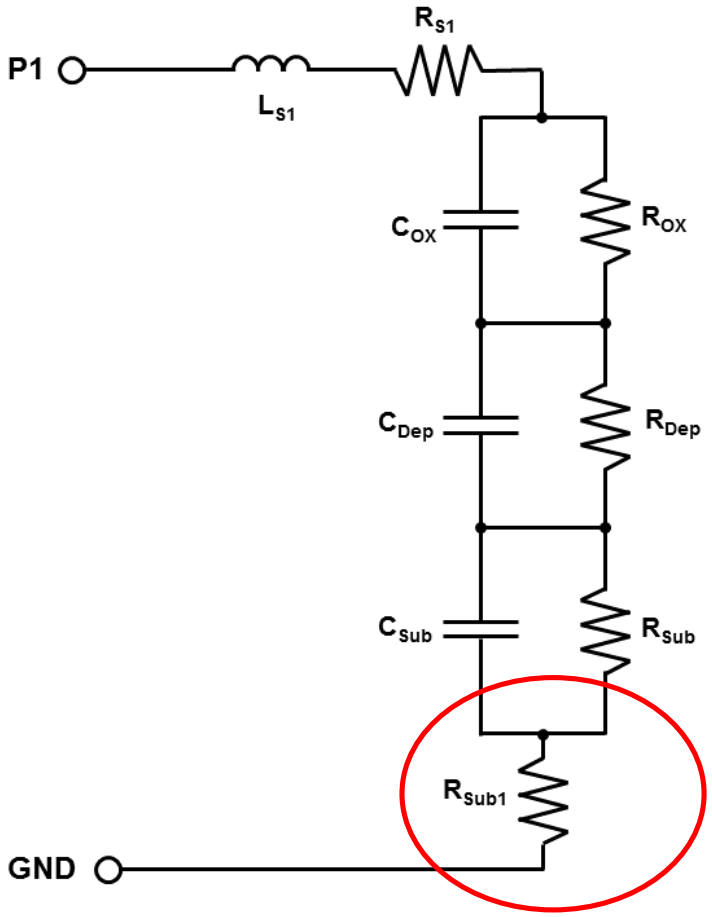
simulation (o) vs. measurement (+)

Isolated TSV: Input Reflection at V=0

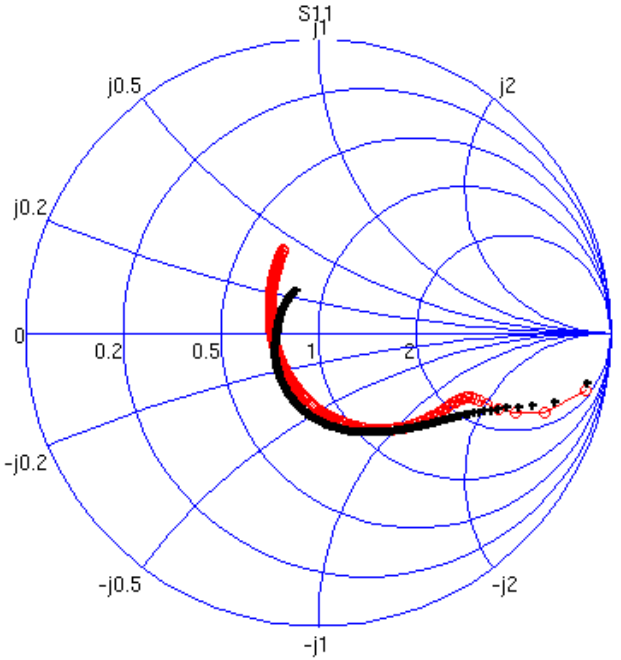
TSV40 Modeling

TSV40





TSV80

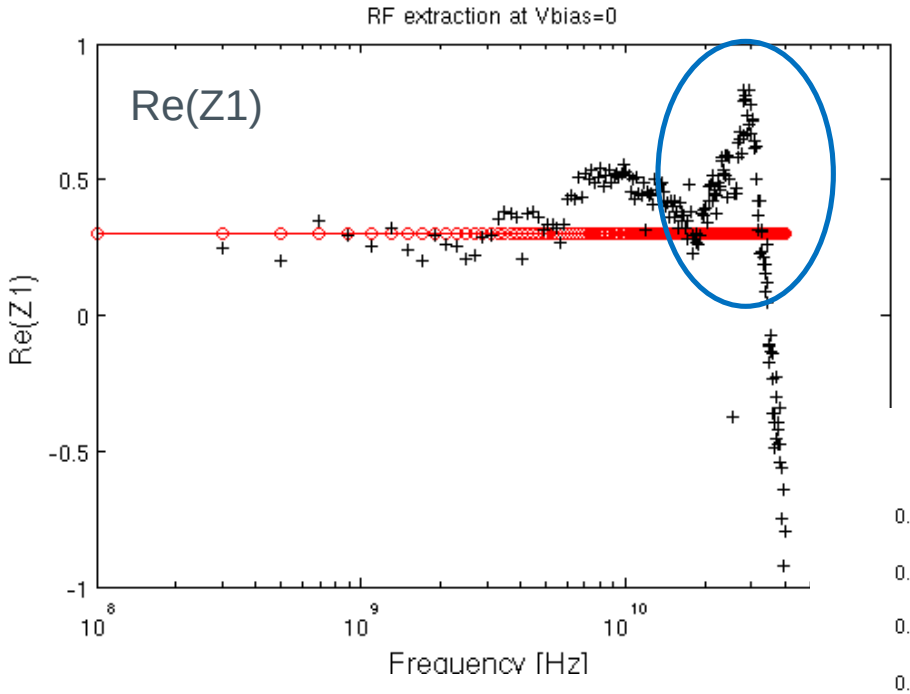


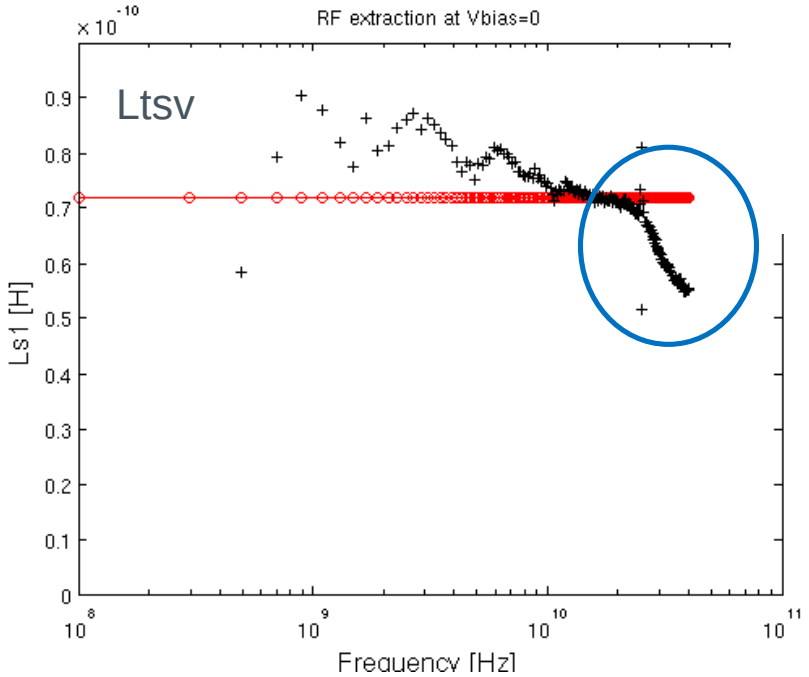
At highest frequencies S11 will reveal Rsub1.

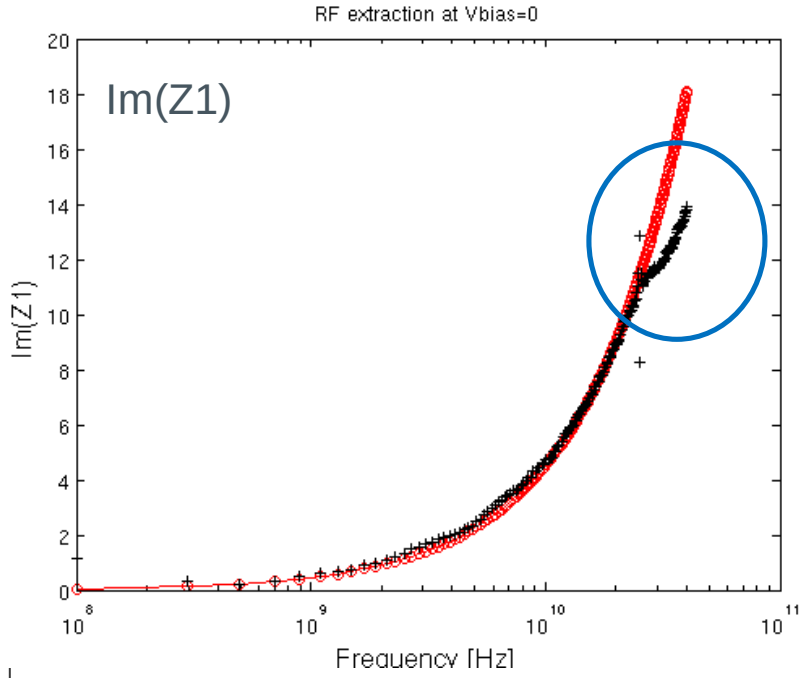
simulation (o) vs. measurement (+)

Single TSV: Wire Impedance

TSV40 Modeling







Skin effect is seen at above 20 GHz.

$Z_1 = Z_{11} - (Z_{12} + Z_{21})/2$

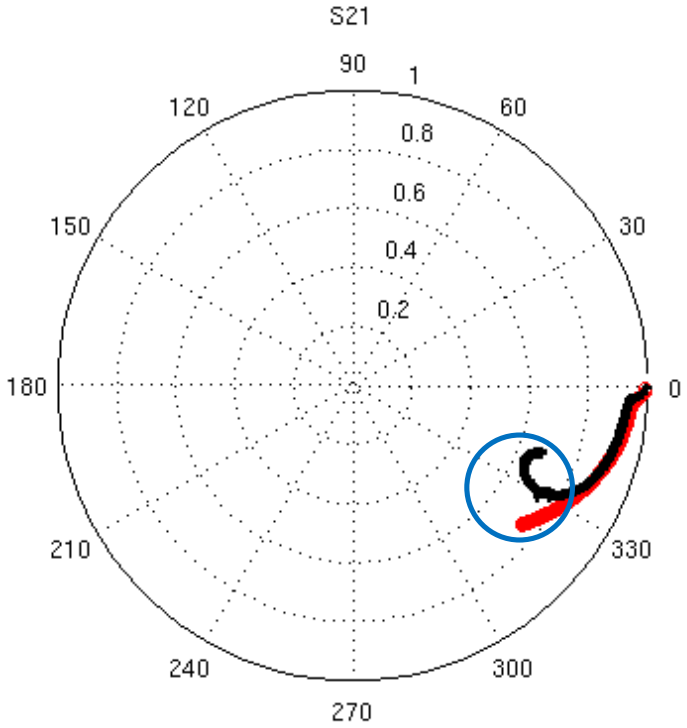
$L_{tsv} = Im(Z_1)/\omega$

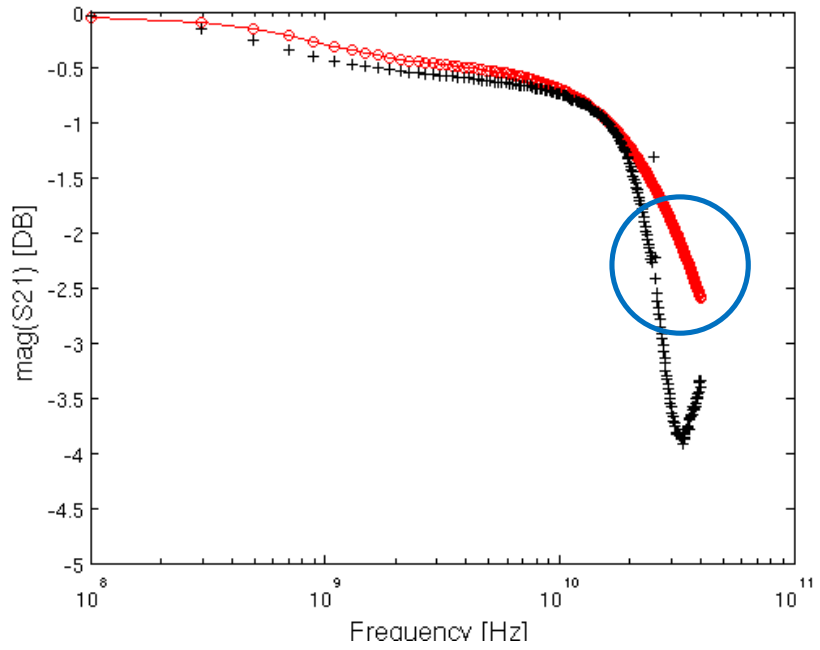
simulation (o) vs. measurement (+)

Single TSV: Forward Transmission at V=0

TSV40 Modeling

S21





At low frequencies all power is transmitted (S21=1).

At high frequencies the skin effect is seen.

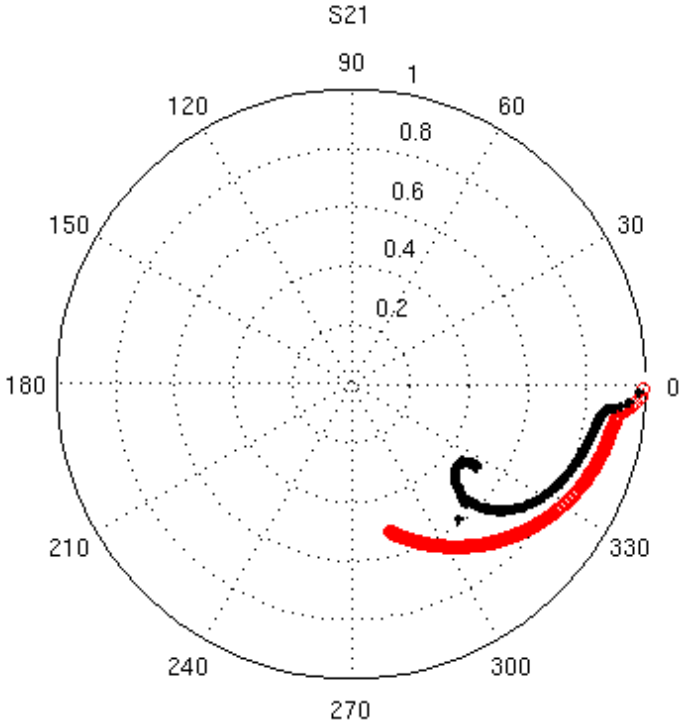
simulation (o) vs. measurement (+)

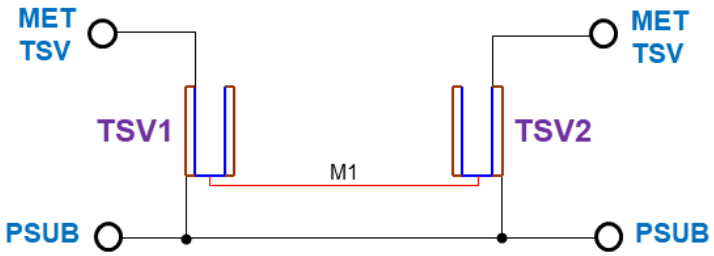
Verification on Connected TSVs

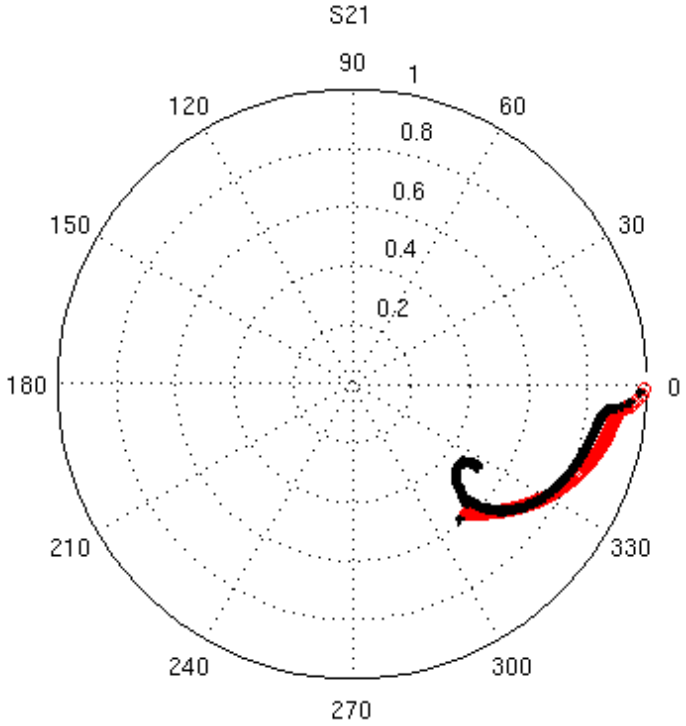
TSV40 Modeling

Rs1/2 and Ls1/2 as extracted on the isolated TSV structure leads to wrong results.

P1 and P2 sees during measurement the same wire inductance and resistance → Rs/2 and Ls/2



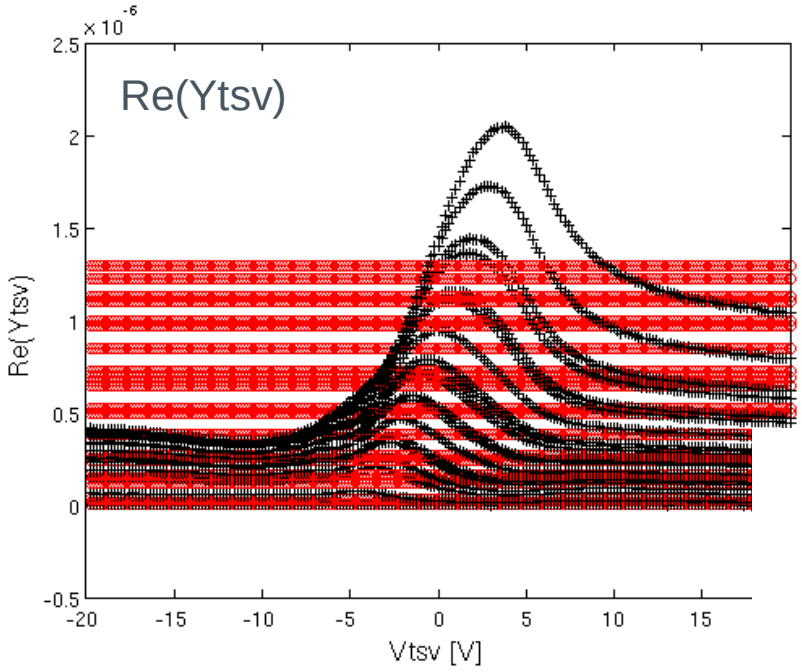


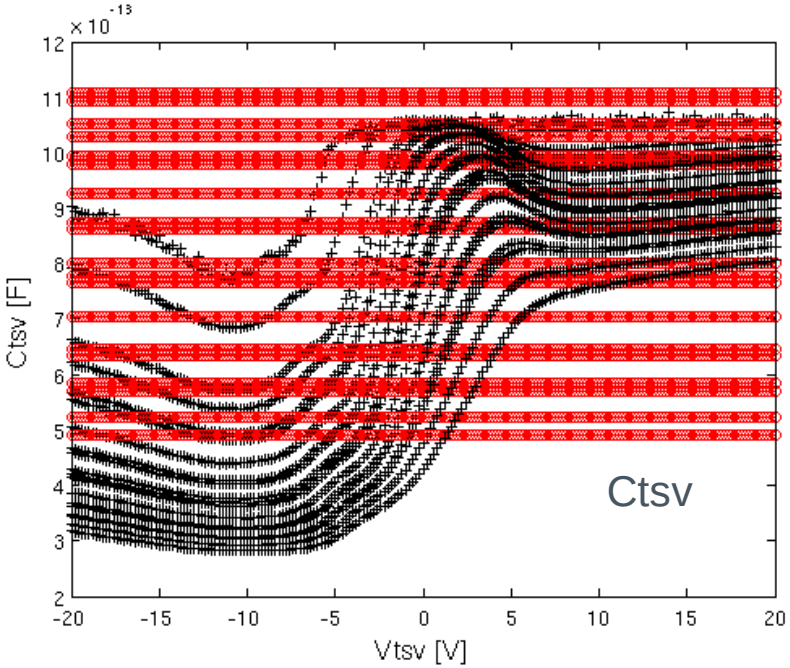


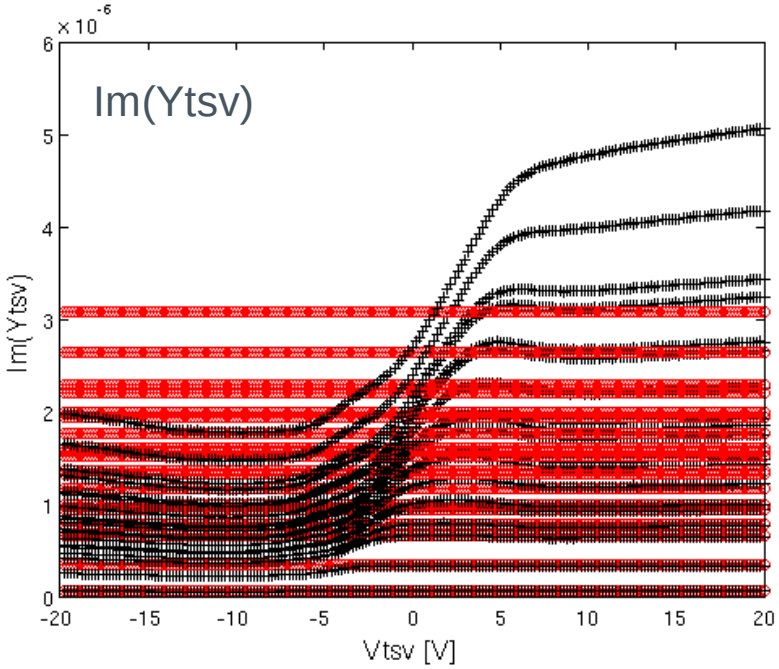
simulation (o) vs. measurement (+)

What to Do with the Bias Dependence?

TSV40 Modeling







f=10 kHz – 1MHz

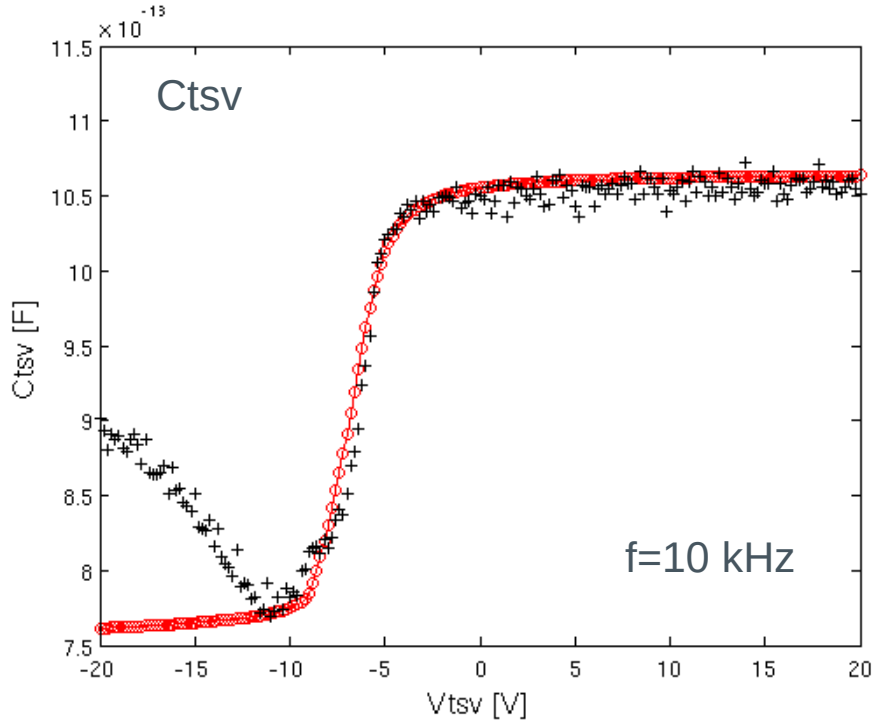
simulation (o) vs. measurement (+)

Subcircuit Extension with MOSVAR

TSV40 Modeling

- Cox in the subcircuit replaced by a MOSVAR model.
- TYPE= -1 (n-type substrate contrary to p-type on silicon)
- Inversion modelled as accumulation.

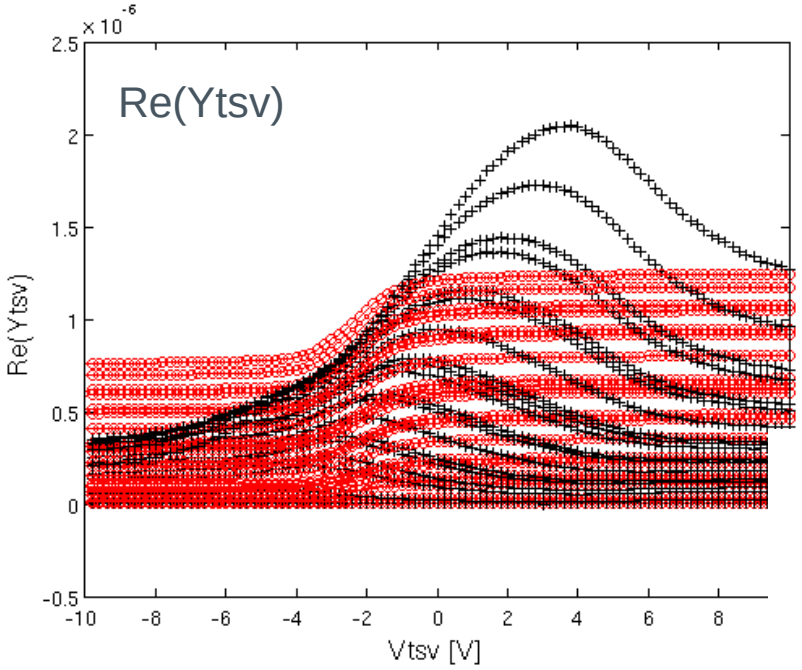
Works at a single frequency.

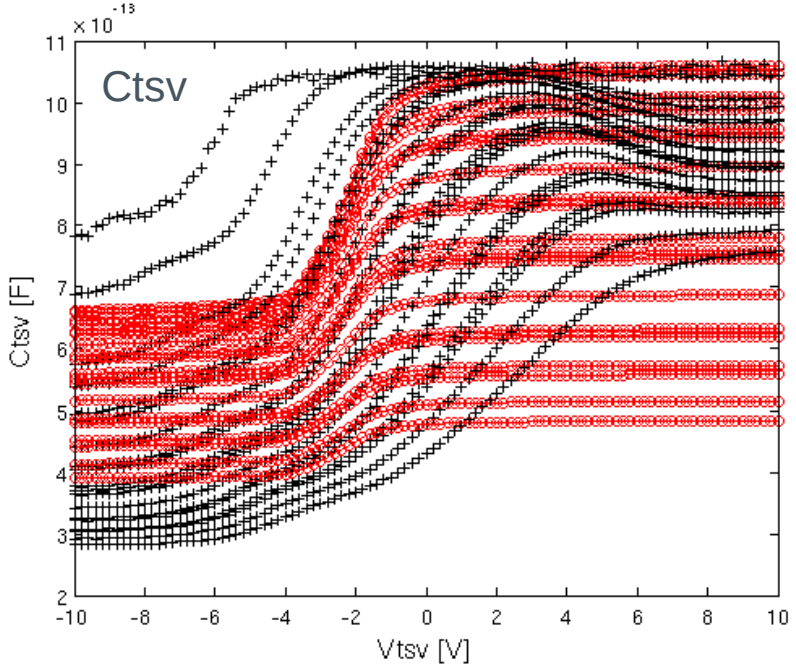


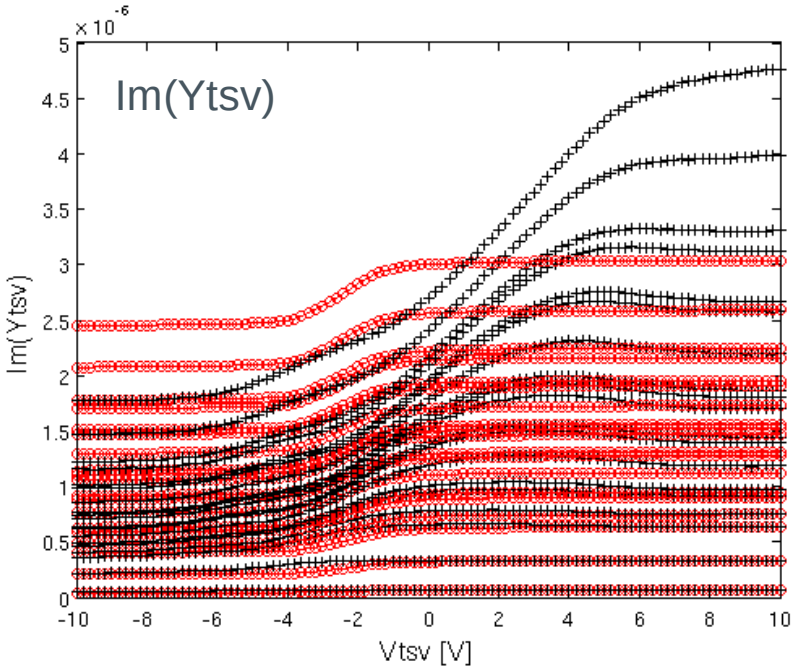
simulation (o) vs. measurement (+)

LCR Measurement vs. MOSVAR Subcircuit

TSV40 Modeling







Limited accuracy at higher frequencies.

f=10 kHz – 1MHz

simulation (o) vs. measurement (+)

Conclusions

TSV Modeling

- Different types of test structures (single, isolated and connected TSVs) were used for model extraction/validation.
- Two measurement domains (LCR meter and VNA) were used. Both of them have to be used for a broadband model extraction valid from kHz to GHz range.
- Results of TSVs having 40u and 80u were shown.
- TSVs show frequency dependence. The developed subcircuit model is valid up to 20 GHz.
- Coupling to substrate requires a complex network to model.
- TSVs may also show bias dependence.
- Bias dependence modeling with the MOSVAR model was investigated.

- **TSVs have their limitations:**
  - Large foot-print.
  - Large frequency dependent parasitics.
  - Frequency dependence can limit noise performance.

Thank you!

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