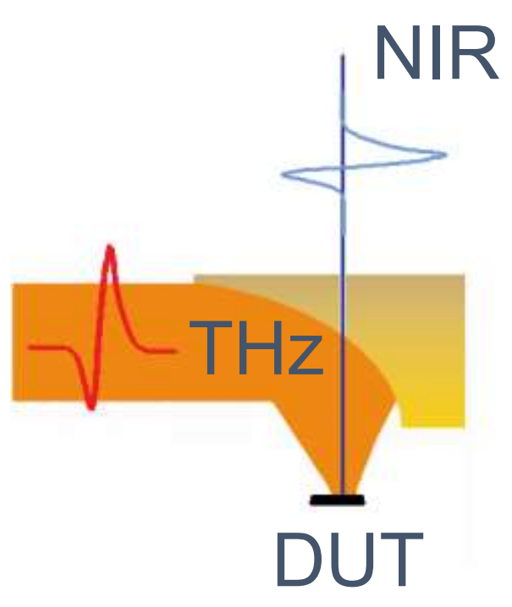
# Optimization of GaAs based field effect transistors for THz detection at particle accelerators

**Rahul Yadav** [1,2], **Stefan Regensburger** [1], **Andreas Penirschke** [2], and **Sascha Preu** [1] **(WEPP23)**
[1] Technische Universität Darmstadt, Germany, [2] Technische Hochschule Mittelhessen, Friedberg (Hessen), Germany

## MOTIVATION

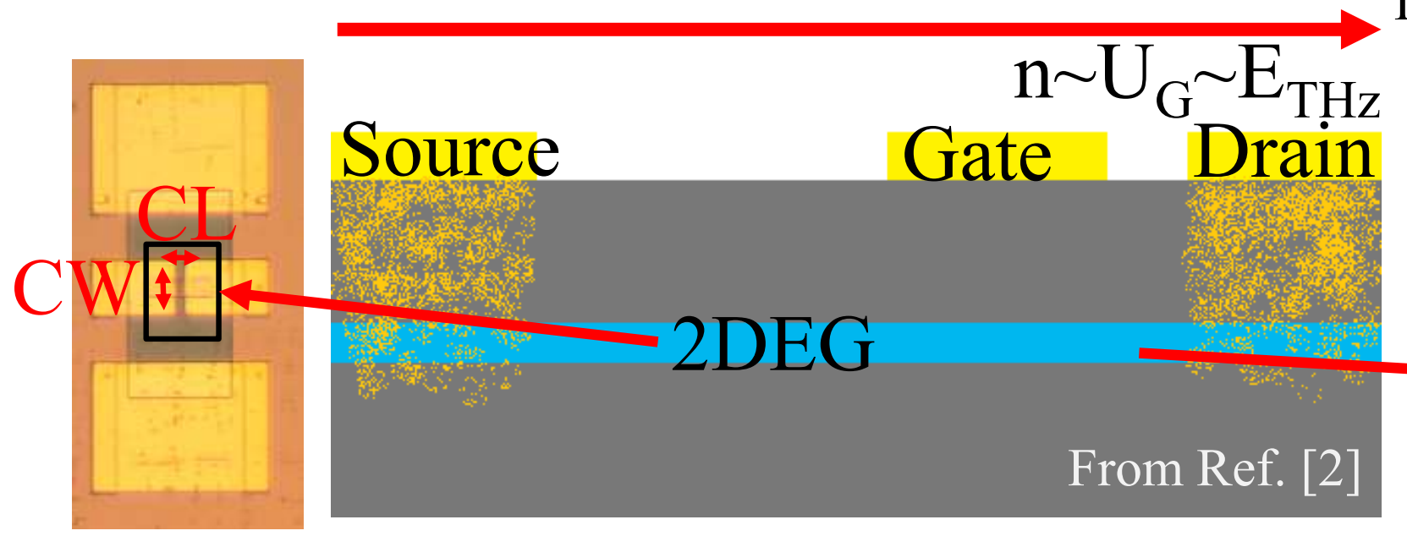
- **Schottky** diodes are faster, but break easily at higher power levels
- No direct locking between free electron laser (FEL) and near infrared (NIR) laser for pump and probe experiments
- Jitter and drift at picosecond scale while synchronizing the repetition rate between FEL and NIR laser
- Roll off at higher frequencies
- Precise on wafer de-embedding



- GaAs based field effect transistor (**FET**) THz detectors:
  - Higher damage threshold compared to Schottky detectors
  - Higher mobility of GaAs compared to other substrates (e.g. GaN)
- Simultaneous detection of amplitude and timing at ps scale for THz and NIR pulses [1]
- Investigation of THz coupling in rectifying elements
- Antenna-coupled and large area FETs are promising candidates

## THEORY OF THz DETECTION WITH FETs

2DEG : Two dimensional electron gas



From Ref. [2]

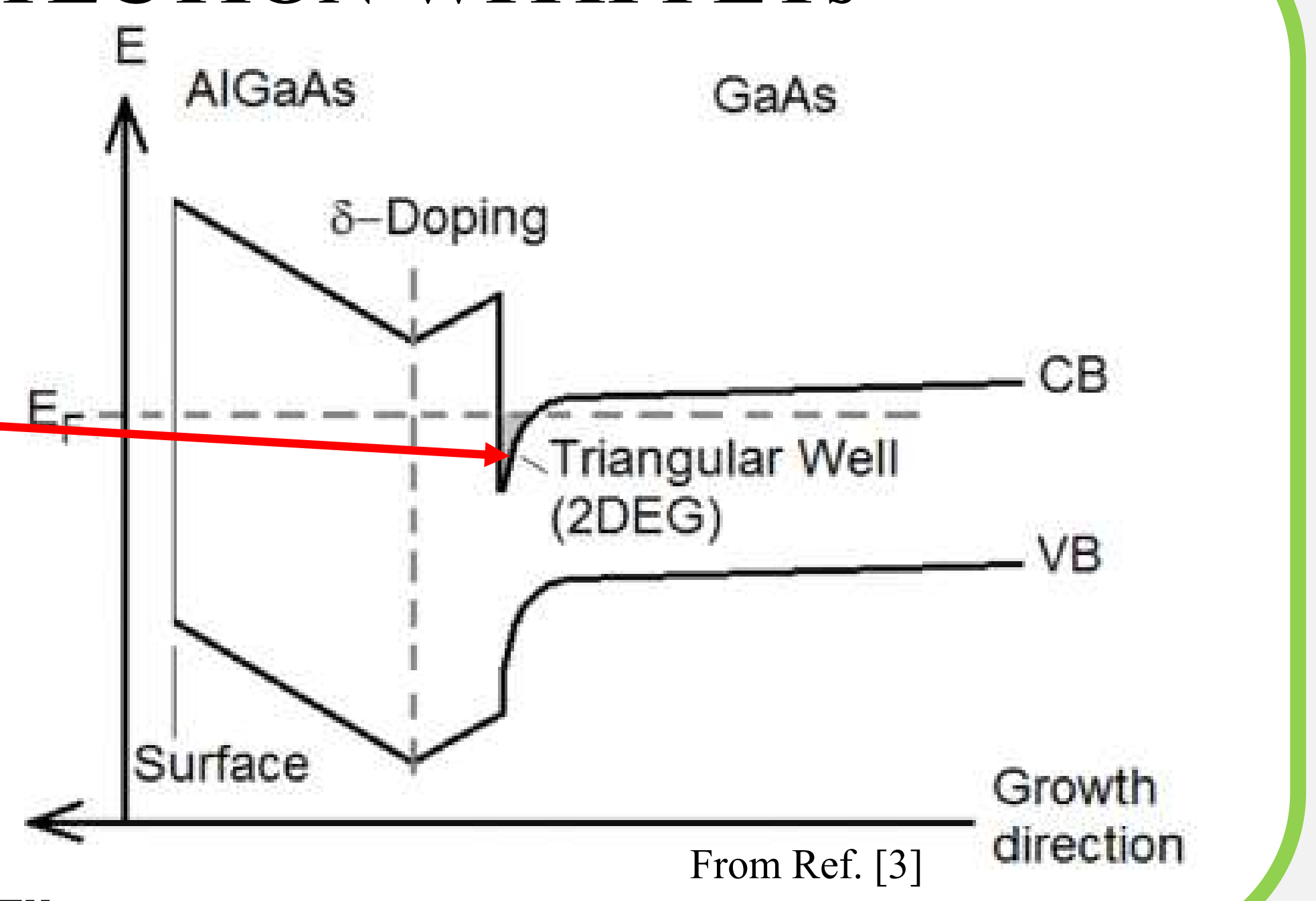
$n^{(2D)} \sim U_G(t) \sim U_{THz}(t)$

$v \sim U_{DS}(t) \sim U_{THz}(t)$

$j = en^{(2D)}(t)v(t) \sim [U_{THz}(t)]^2$
$= [U_{THz,0}]^2 \cdot (1+\cos(2\omega_{THz}t))$

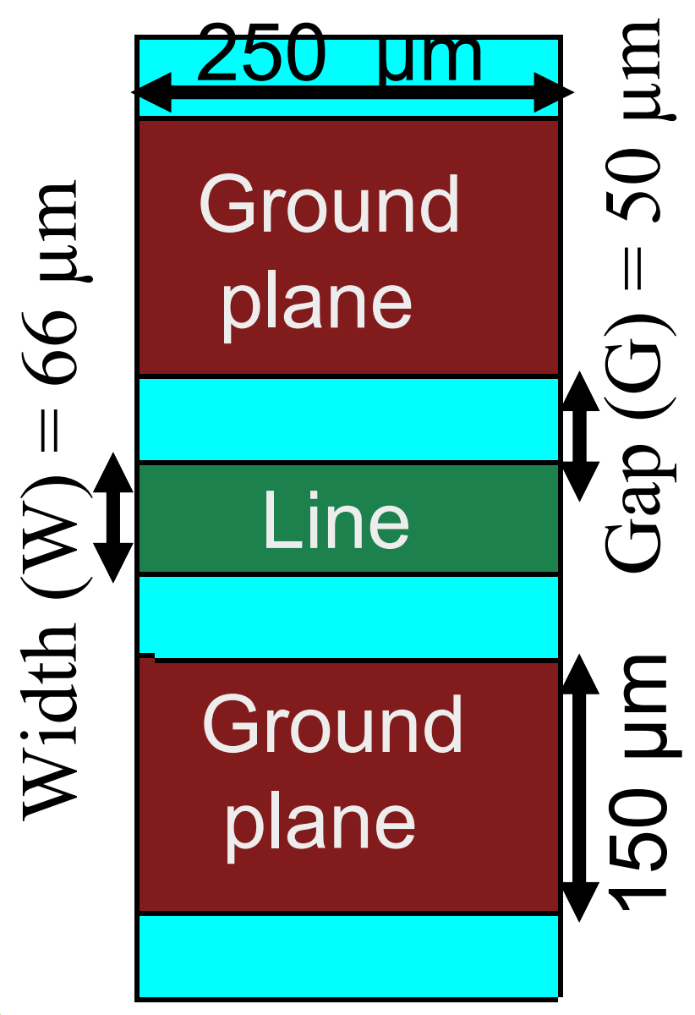
DC component $\sim [U_{THz,0}]^2 \sim P_{THz}$

CW = Channel width
CL = Channel length

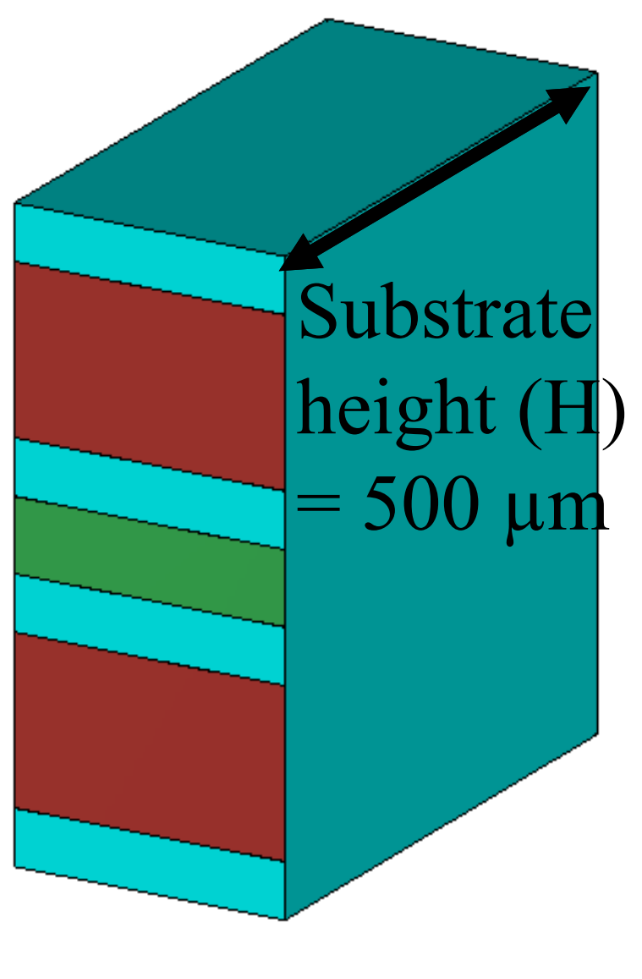


From Ref. [3]

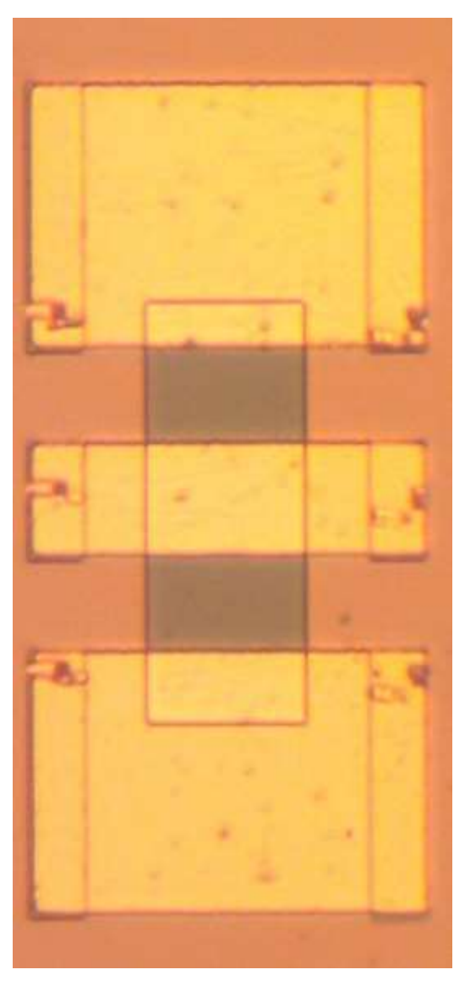
## FABRICATED AND SIMULATED DEVICES



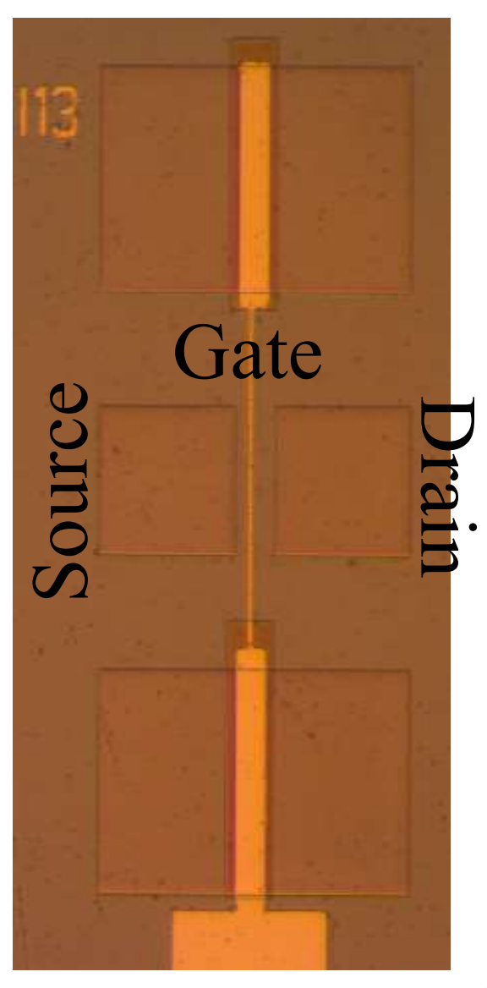
Top view



3D view



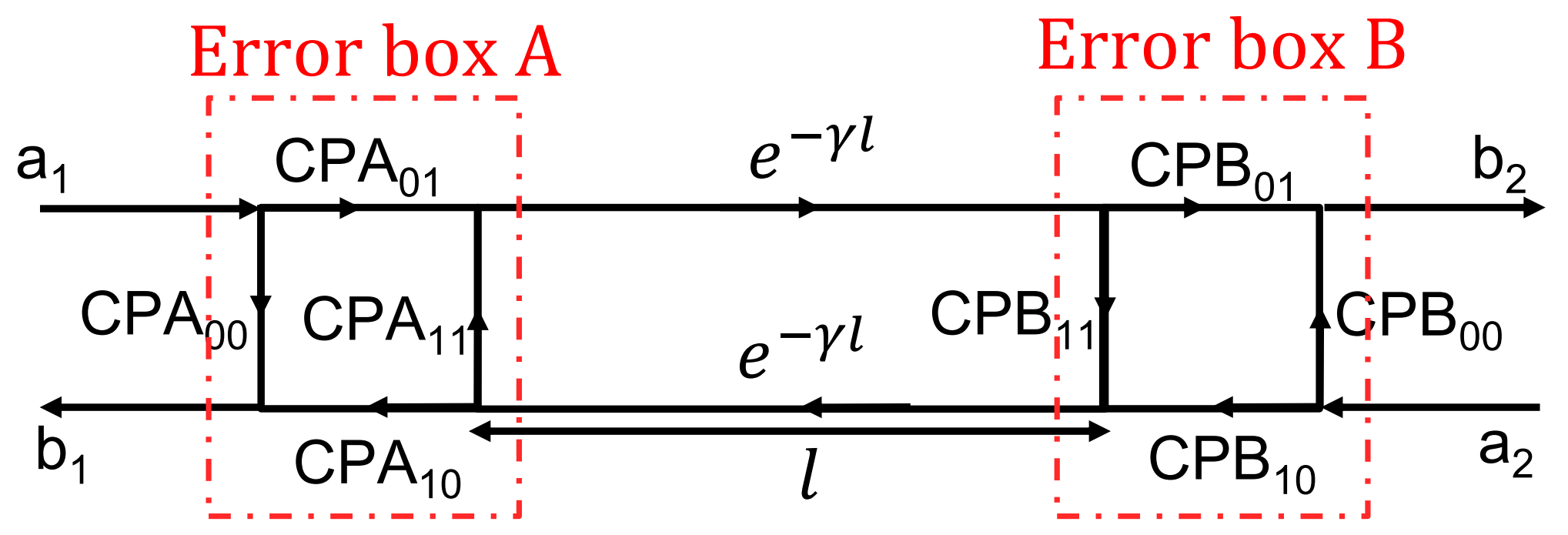
Calibration structure



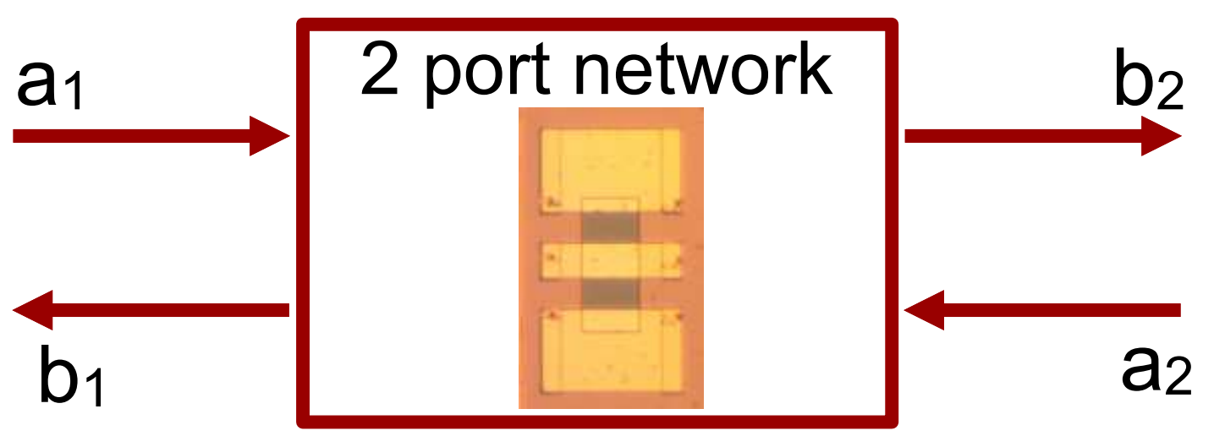
FET device

## DEVICE CHARACTERIZATION BY S-PARAMETERS

- Transmission ($S_{21}$) and Reflection ($S_{11}$) coefficients
- Fast, simple, analytical and more accurate method for device characterization at higher frequencies
- Derivation of lumped elements of a transmission line



Signal flow graph of transmission line including error boxes A and B



$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

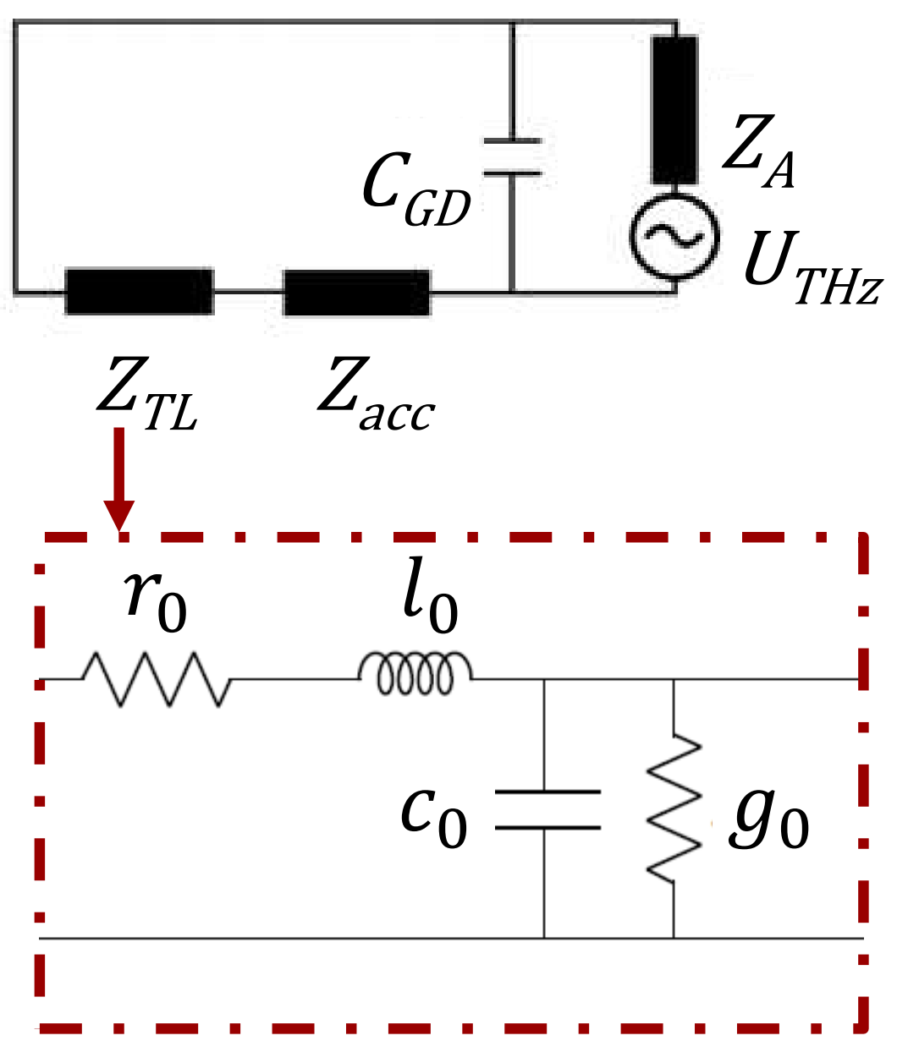
From Ref. [4]

Lumped elements equivalent circuit of FETs

$$\frac{\partial U_{THz}}{\partial x} = -(r_0 + j\omega l_0) I_{THz}(x)$$

$$\frac{\partial I_{THz}}{\partial x} = -(g_0 + j\omega c_0) U_{THz}(x)$$

$$\gamma = \pm\sqrt{(r_0 + j\omega l_0)(g_0 + j\omega c_0)} \quad Z_{TL} = \sqrt{\frac{(r_0 + j\omega l_0)}{(g_0 + j\omega c_0)}}$$

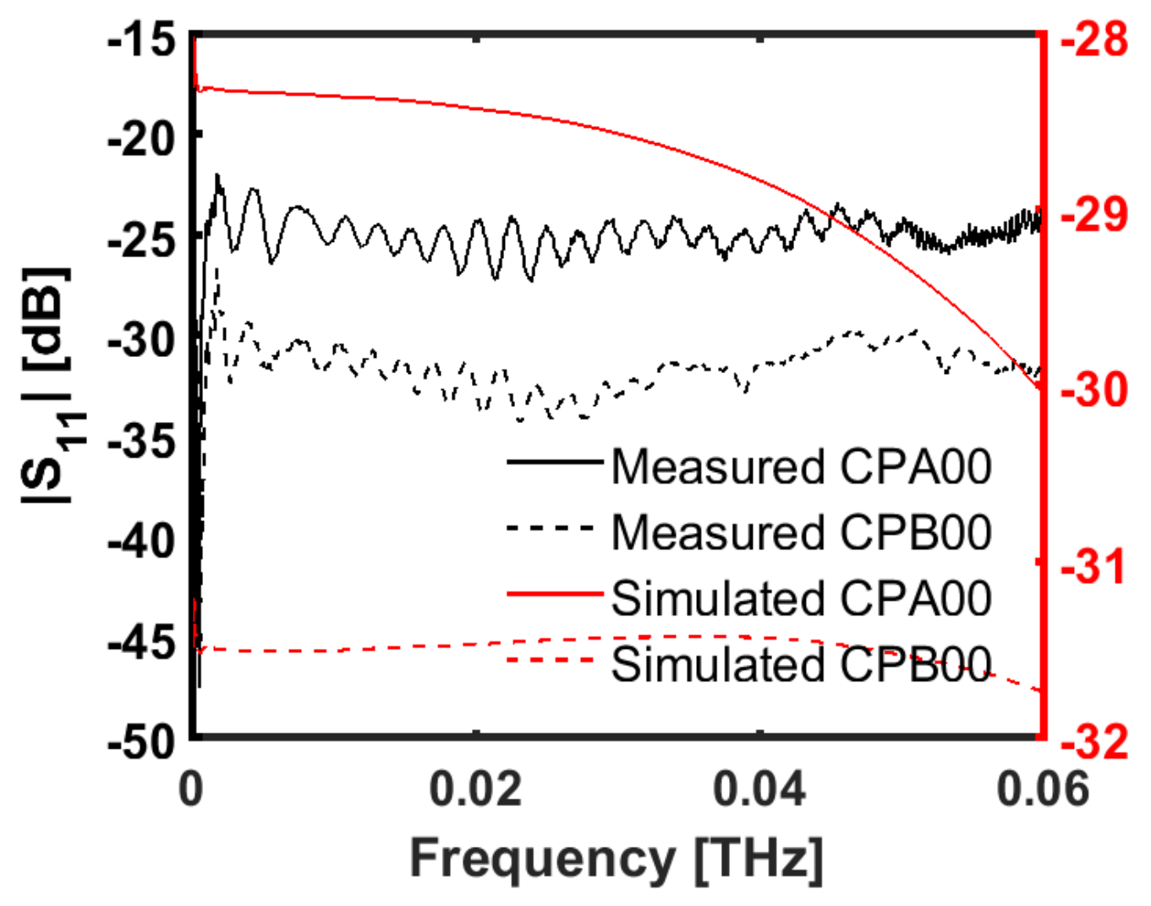


$\gamma$ = propagation constant
$r_0$ = resistance/length
$g_0$ = conductance/length
$c_0$ = capacitance/length
$l_0$ = inductance/length
$Z_{TL}$ = Impedance of transmission line

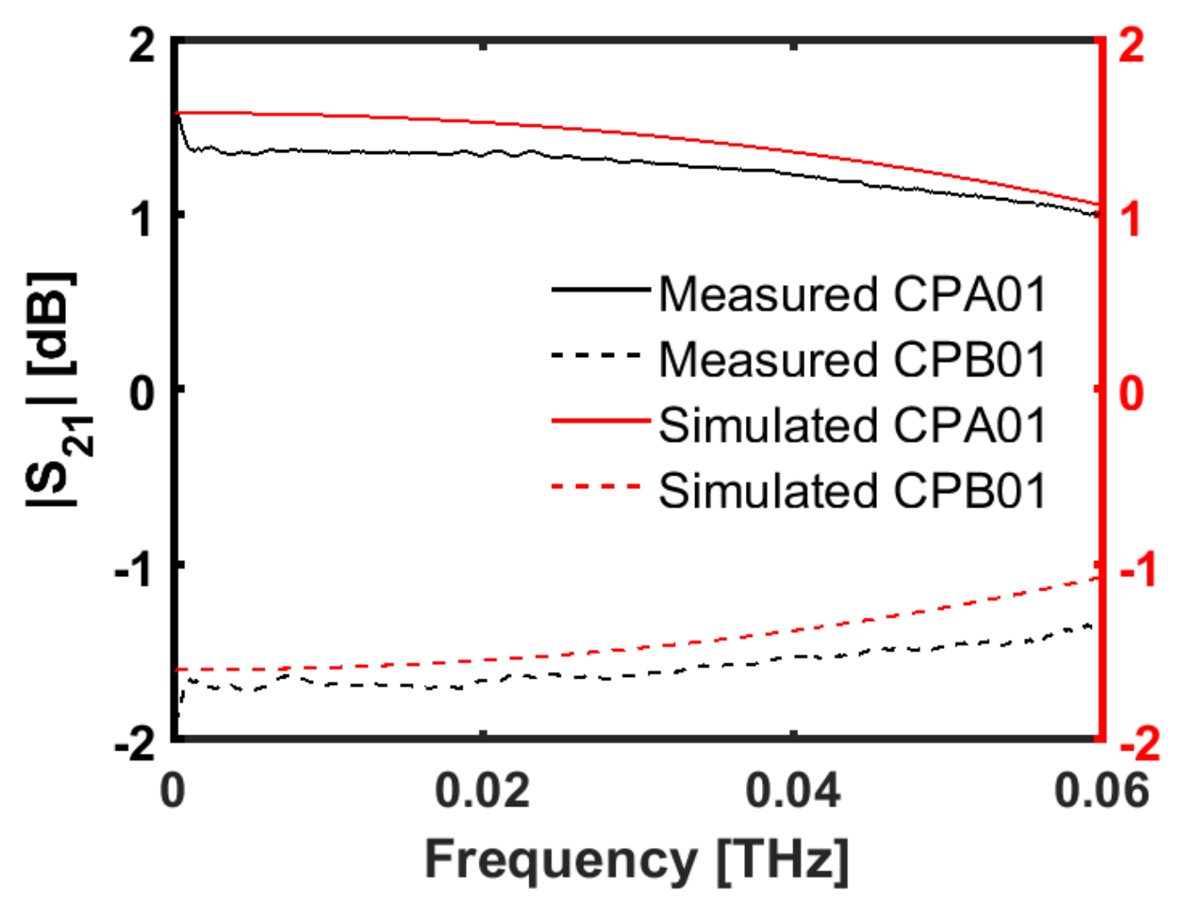
$U_{THz}$ = THz bias
$C_{GD}$ = Gate-Drain capacitance
$Z_A$ = Antenna radiation impedance
$Z_{acc}$ = Access impedance due to ungated part

## RESULTS

Reflection coefficient

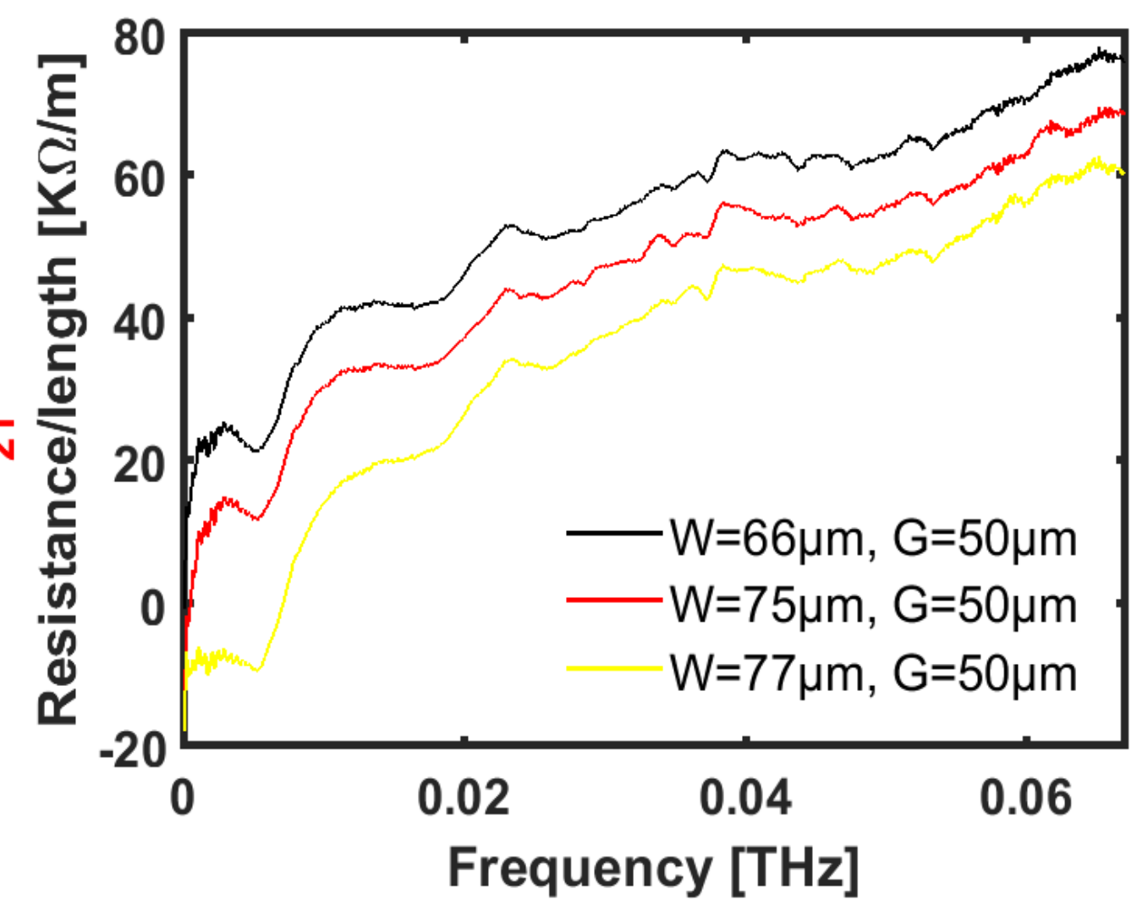


Transmission coefficient



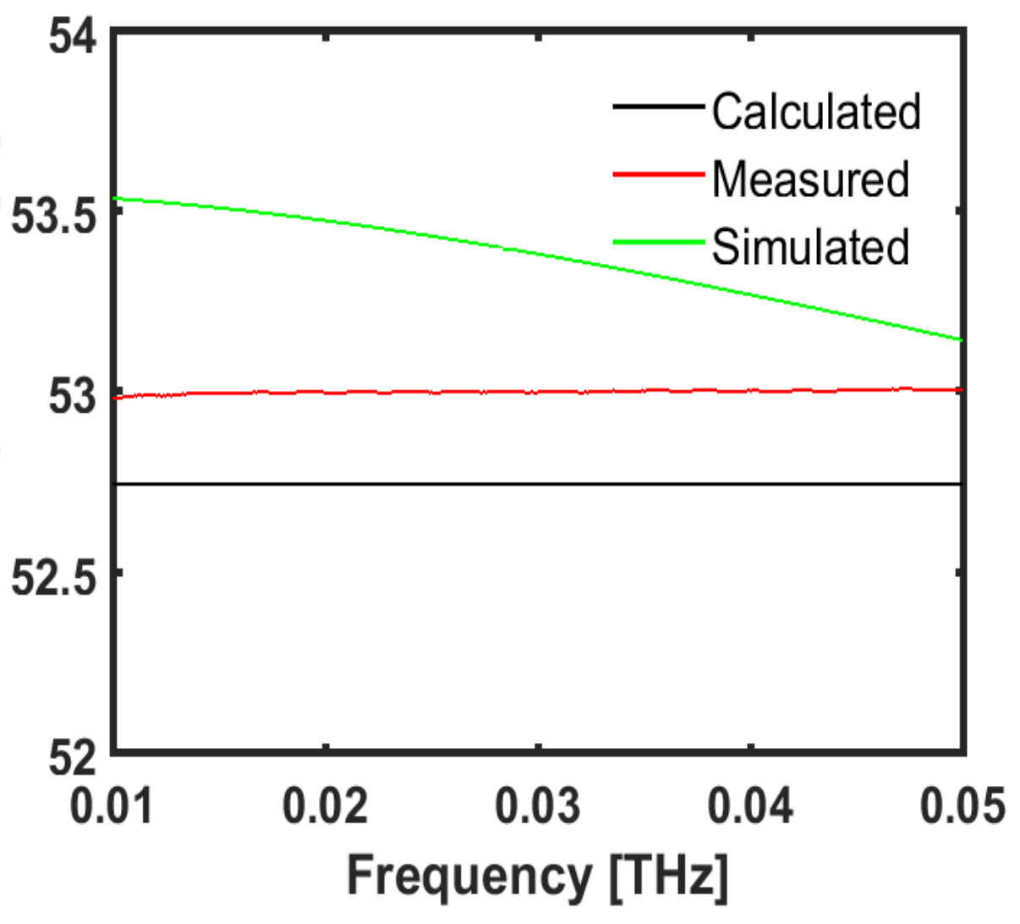
On wafer TRL de-embedding and error boxes CPA and CPB calculation [5]

Resistance $(r_0/l)$

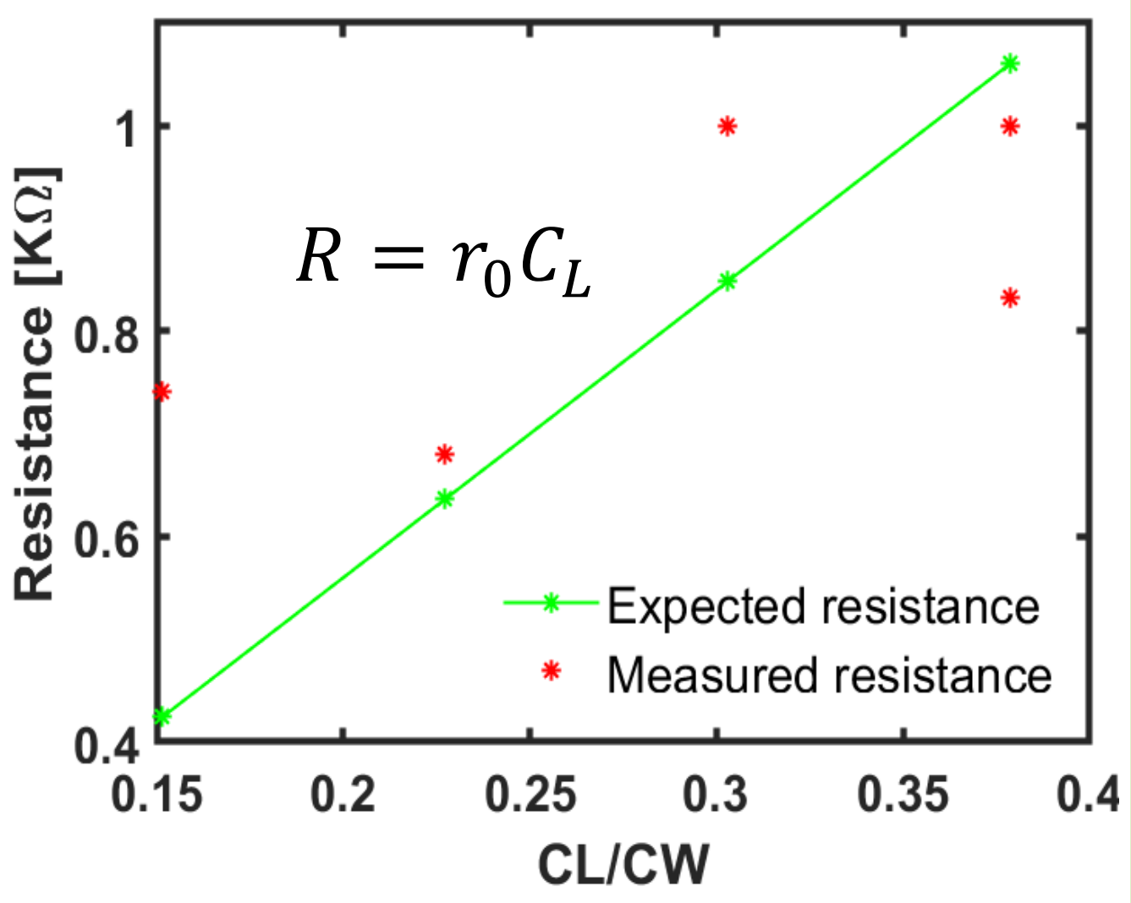


Derivation of $r_0$ for coplanar waveguide (CPW) with constant $G$ and variable $W$

Line Impedance



2DEG channel width of 66 µm



Good agreement between expected and measured values

## CONCLUSION AND OUTLOOK

- Simulations fit to measurements
- On wafer TRL de-embedding performed successfully
- DC resistance of CL/CW is in agreement with expected values
- Value of lumped elements calculated for transmission line
- Lumped elements' values for 2DEG is under investigation
- Results will help in optimizing future FETs for accelerator applications

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## REFERENCES

[1] Regensburger, Stefan, et al. "Broadband THz detection from 0.1 to 22 THz with large area field-effect transistors." *Optics express* 23.16 (2015): 20732-20742'.
[2] Preu, S., et al. "An improved model for non-resonant terahertz detection in field-effect transistors." Journal of Applied Physics 111.2 (2012): 024502.
[3] Regensburger, Stefan, et al. "Broadband Terahertz Detection With Zero-Bias Field-Effect Transistors Between 100 GHz and 11.8 THz With a Noise Equivalent Power of 250 pW/$\sqrt{Hz}$ at 0.6 THz." *IEEE Transactions on Terahertz Science and Technology* 8.4 (2018): 465-471.
[4] Cascade microtech, user guide for 'On wafer VNA measurements.
[5] Guoping, Tang, et al. "On-wafer de-embedding techniques from 0.1 to 110 GHz." *Journal of Semiconductors* 36.5 (2015): 054012.