SWTEST

PROBE TODAY, FOR TOMORROW

2022 CONFERENCE

CONTACTLESS MEASUREMENT OF VOLTAGE DISTRIBUTION IN RF SWITCHES AT HIGH SPATIAL RESOLUTION

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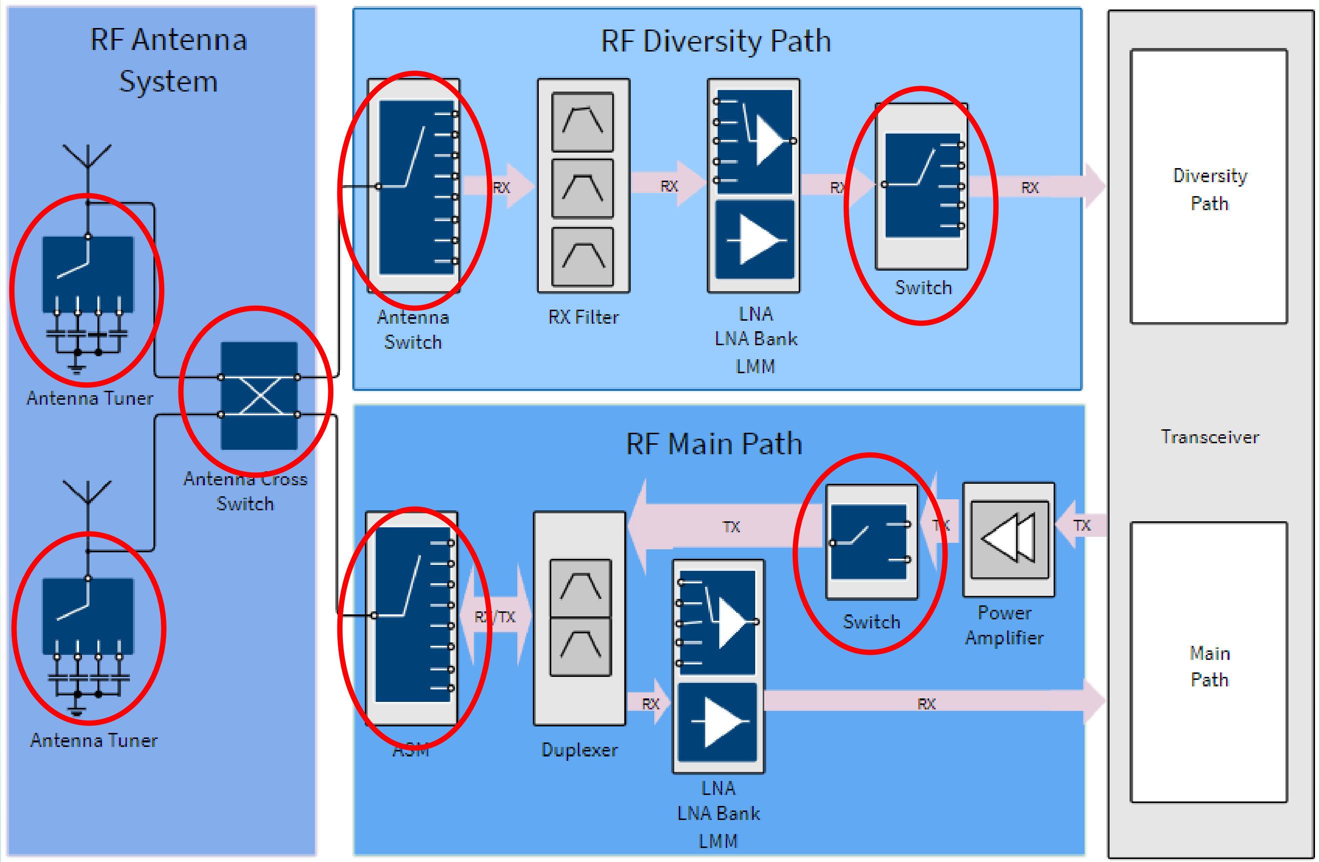
Background

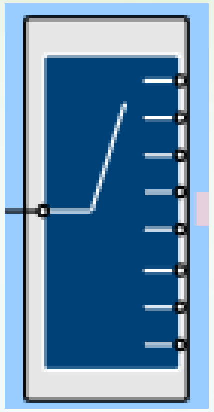
- **RF Front end module**
- **Fulfilling versatile tasks**
  - Impedance matching
  - Filtering and amplification
  - Signal routing and switching
- **RF-switches are crucial components of front end modules**

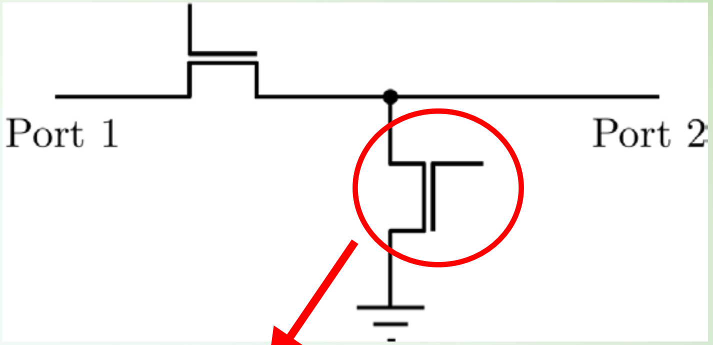


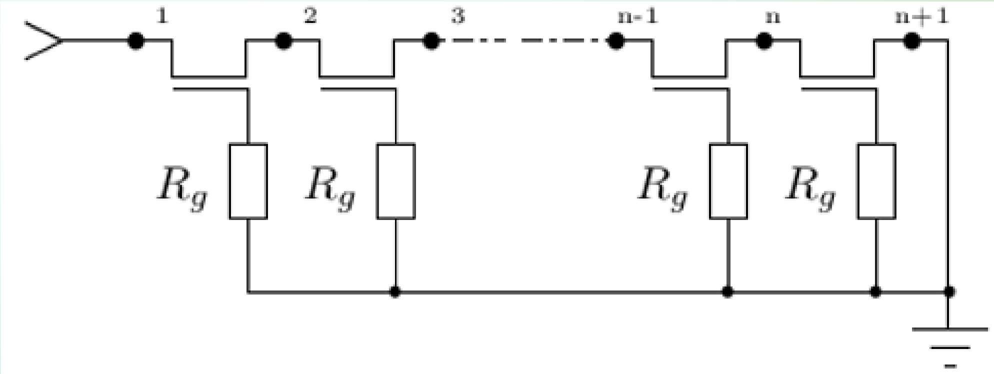
[https://www.infineon.com/cms/de/applications/consumer/mobile-devices/rf-front-end/]

RF Switches

- **Requirements**
  - Insertion loss
  - Isolation
  - Linearity (harmonics)
  - Power handling capabilility
    → stacked FET switches



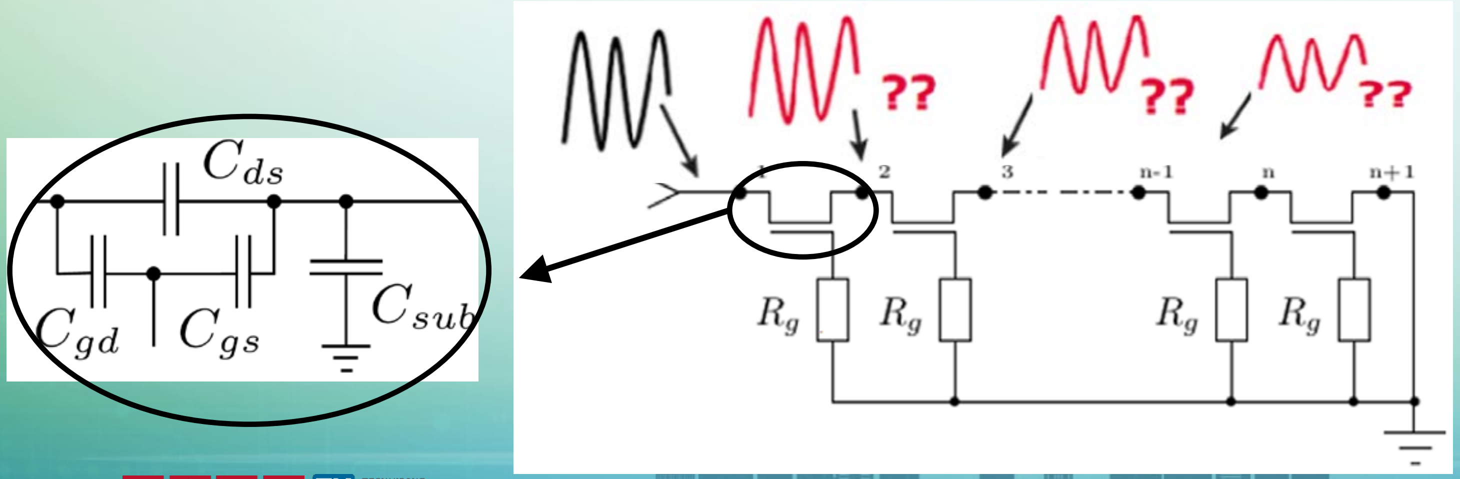


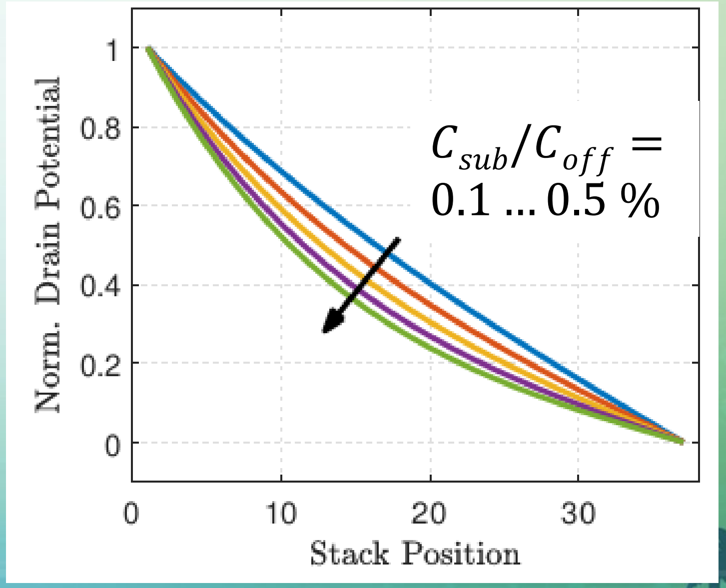


Voltage distribution in stack

- **Even voltage distribution desired → same voltage drop on each FET**
- **Uneven voltage distribution due to parasitc effects limits power handling capability and linearity**
- **Simplified model**
  - Off-state capacitance $C_{off} = C_{ds} + C_{gd}||C_{gs}$
  - Parasitic substrate capacitances C_{sub}
  - Voltage distribution depending on C_{sub}/C_{off}

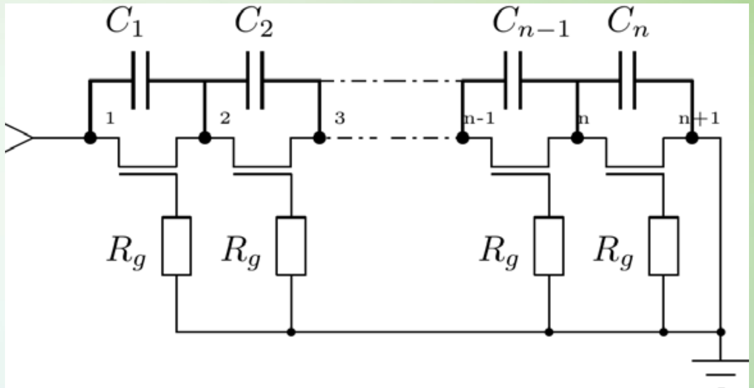
Example:
$C_{off} = 1pF$, $C_{sub} = 1 \ldots 5fF$

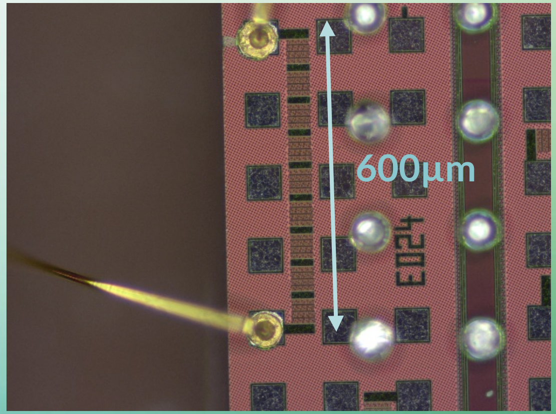




Measurement of voltage distribution

- **Compensation possible if parasitics are known**
  - Feedforward capacitances to compensate known nonlinear distribution
- **Transistor size (distance between drain/source electrodes): 5-20 µm**
- **How to determine voltage distribution?**
  - EM-simulations - *complexity, accuracy*
  - Contact-based probing *- size*
  - In-circuit measurements - *size*
  - Analysis of harmonics - *Input/output-based*

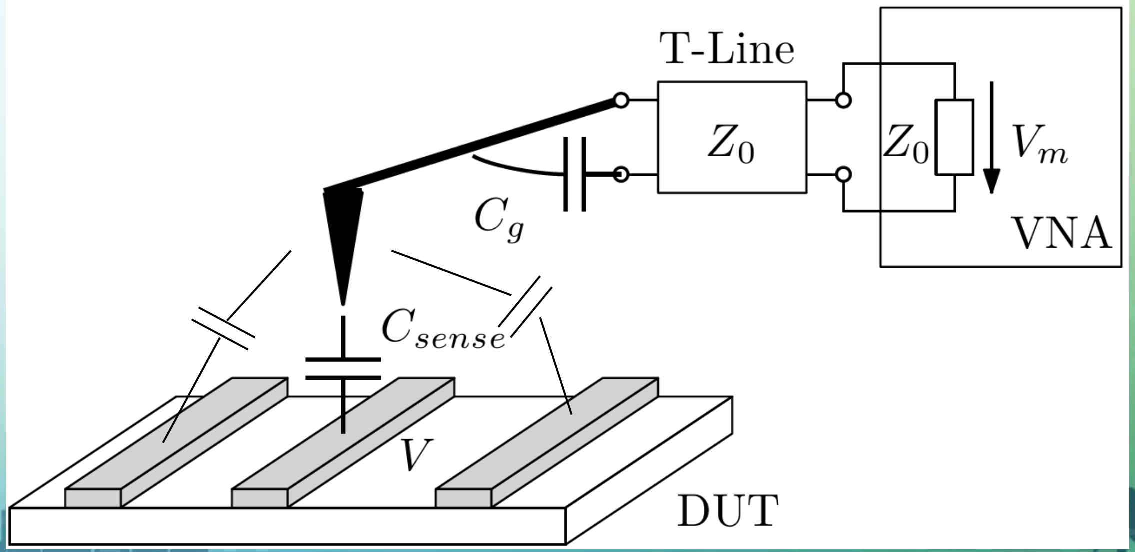




Stacked RF-switch

Contactless measurement

- Approach: Contactless measurement of RF voltages (Electric Field Probing)
- Capacitively coupled probe positioned at defined distance to test points (i.e. drain electrodes of switch)
- Measure signal transmitted via probe
- Performance
  - Spatial resolution (crosstalk) ?
  - Voltage resolution (SNR) ?



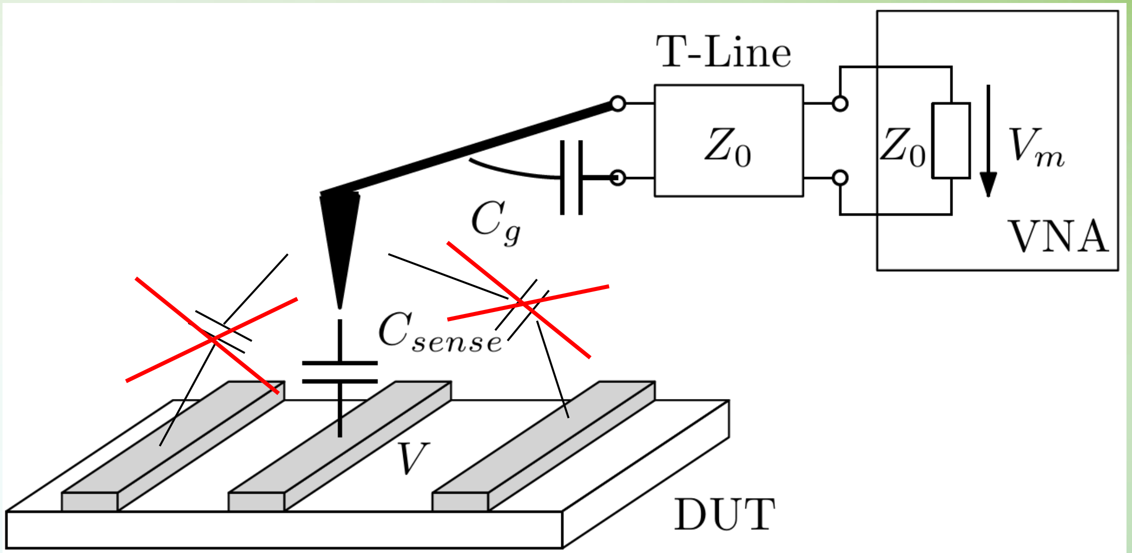
Measurement concept

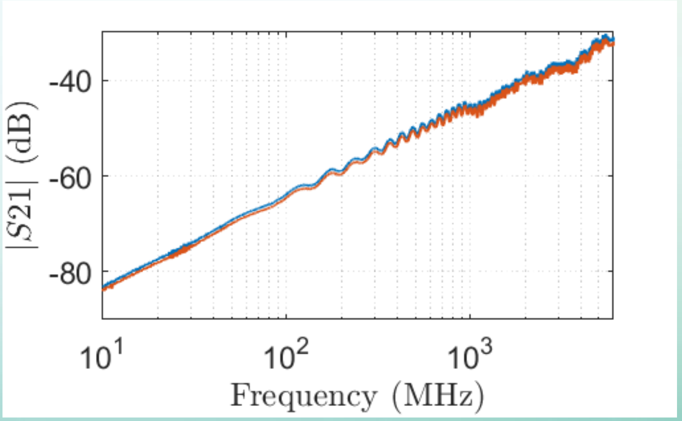
- **Transfer function**

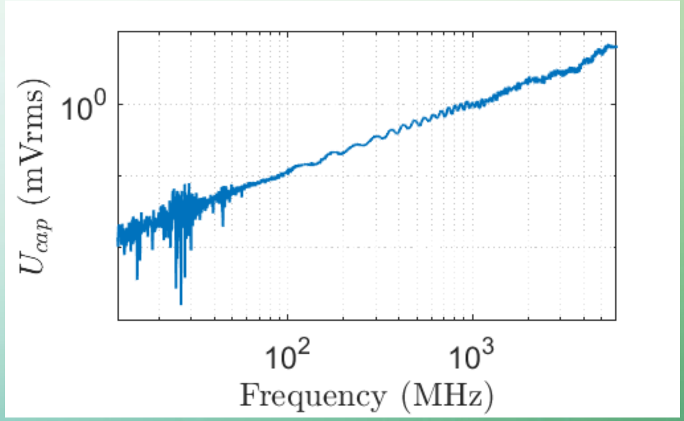
$$\frac{V_m}{V} = \frac{j\omega Z_0 C_{sense}}{1 + j\omega Z_0 (C_{sense} + C_g)}$$

- **Differential measurement to reduce crosstalk**

$$\Delta V_m = V_m(z_1) - V_m(z_2)$$
$$\approx \boldsymbol{V} \cdot \Delta C_{sense}(z) \cdot j\omega Z_0$$

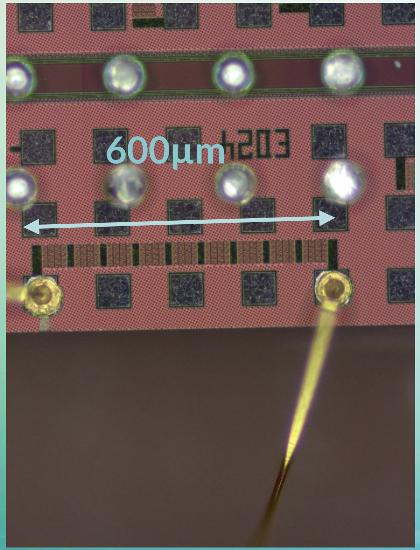


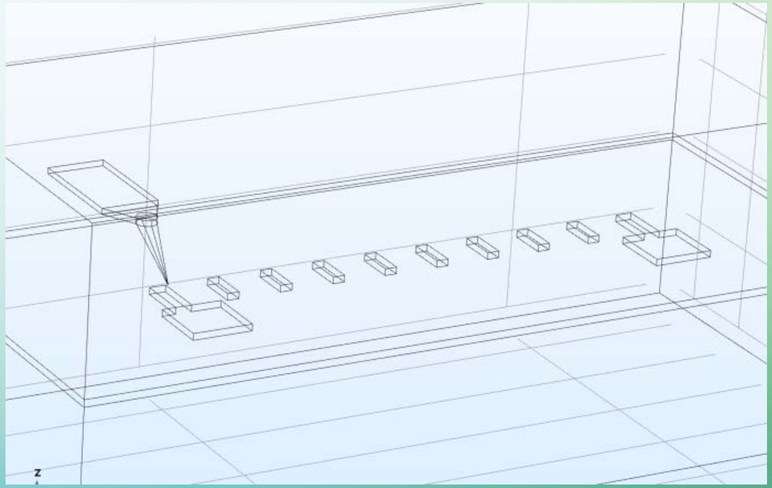




Probe selection

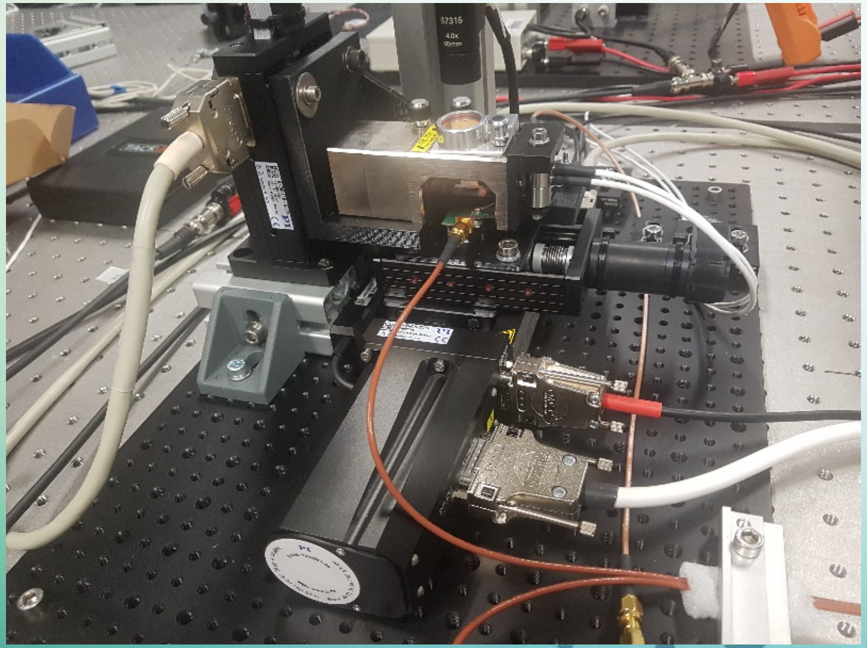
- Sharp tip with radius ≪ test point size
- Accurate tip-surface capacitance (→ distance) control
- Bonded devices → high aspect ratio
- Conductive cantilever probe (RMNano)

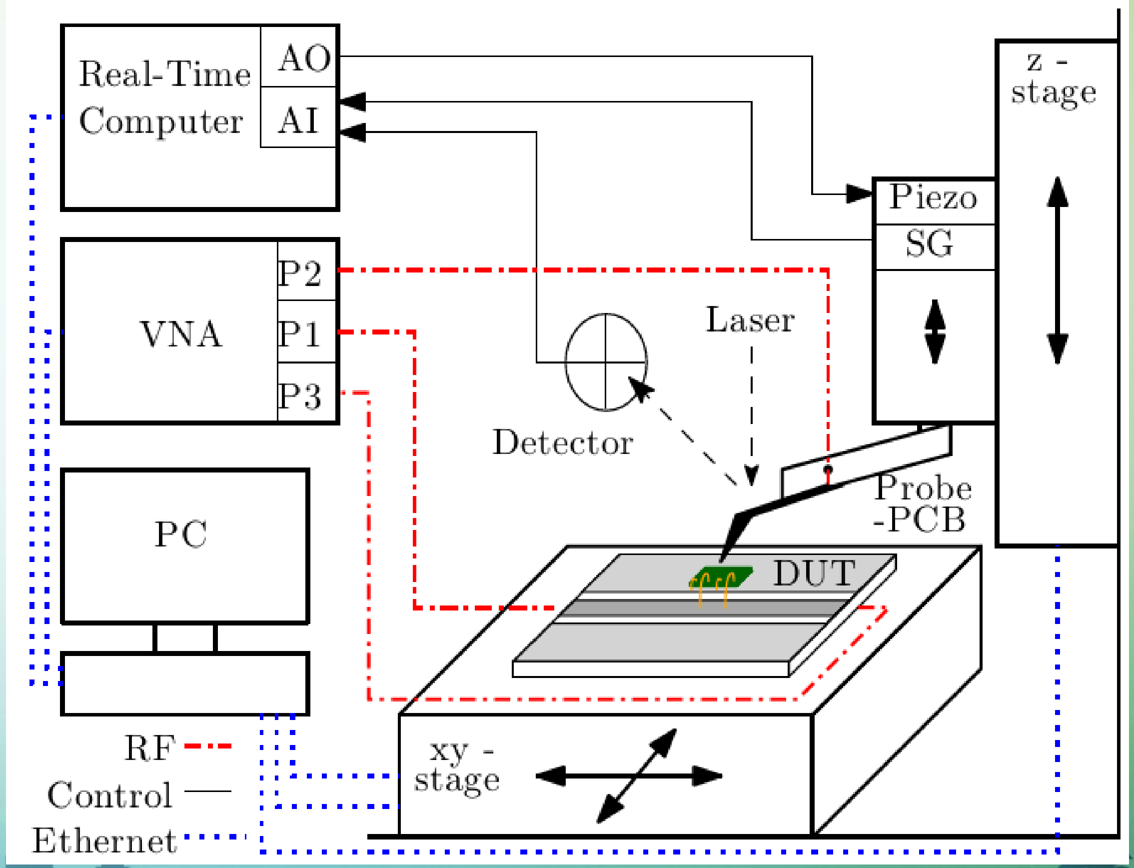




Implementation

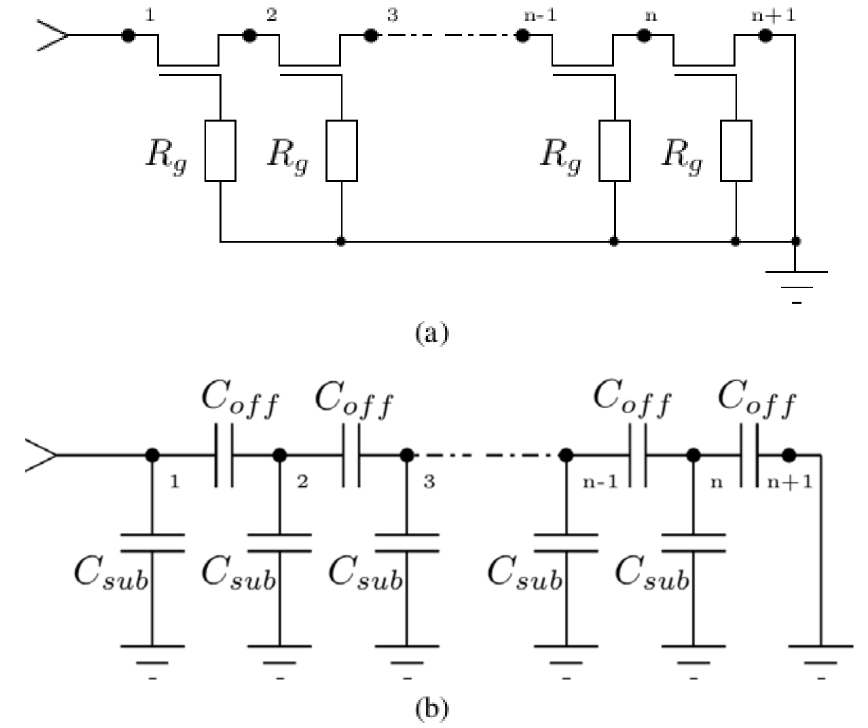
- Dual-stage probe positioning system with 25 mm range and < 10 nm resolution
- Optical deflection measurement (Atomic Force Microscopy)

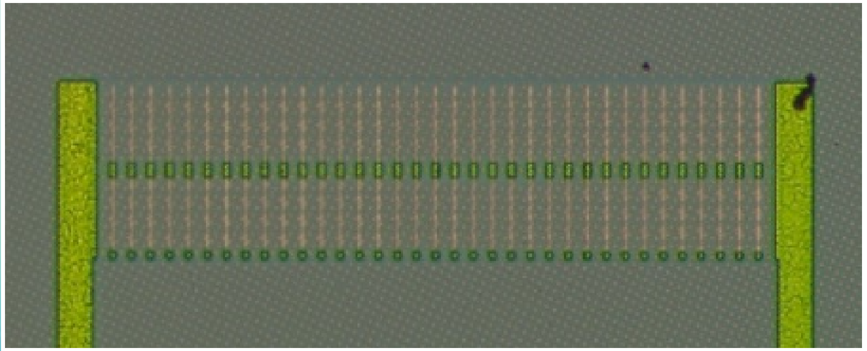




Device under test

- RF switch wit n = 36 identical FETs
- Test points on drain metals for defined coupling capacitance
- Test point size: 2.4 x 8 µm
- Distance of 10 µm between test points
- Passivated surface (~1 µm thickness)
- Bonded to microstrip line on PCB





Tip-circuit capacitance

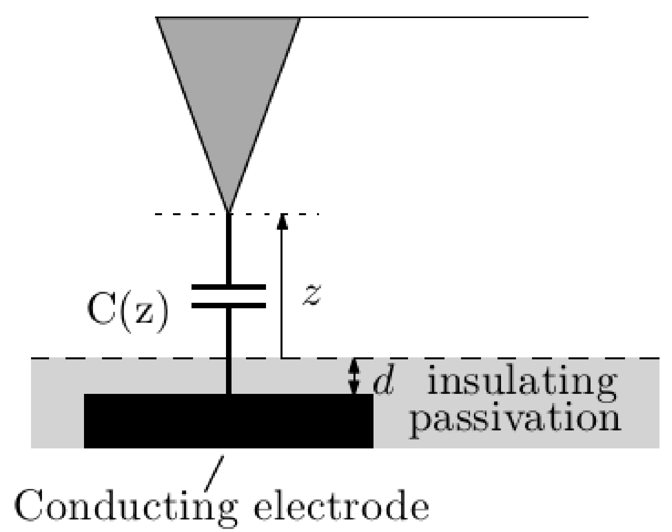
- **Identification of capacitance vs. distance relation**
- **Measured on individual test point with known RF voltage**
- **Modelled capacitance of test point to tip:**

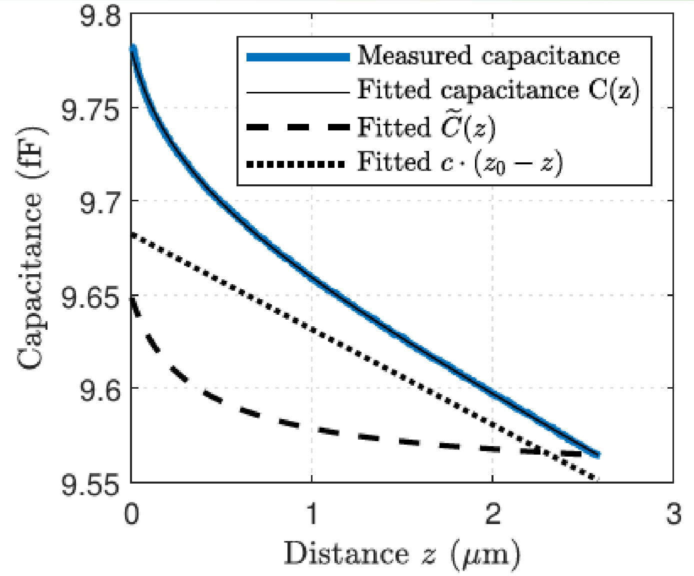
$$C(z) = \tilde{C}(z) + c(z_0 - z) + C_0$$

  - Nonlinear capacitance to apex (short-range):

$$\tilde{C}(z) = A \cdot \ln\left(1 + \frac{B}{z + C}\right)$$

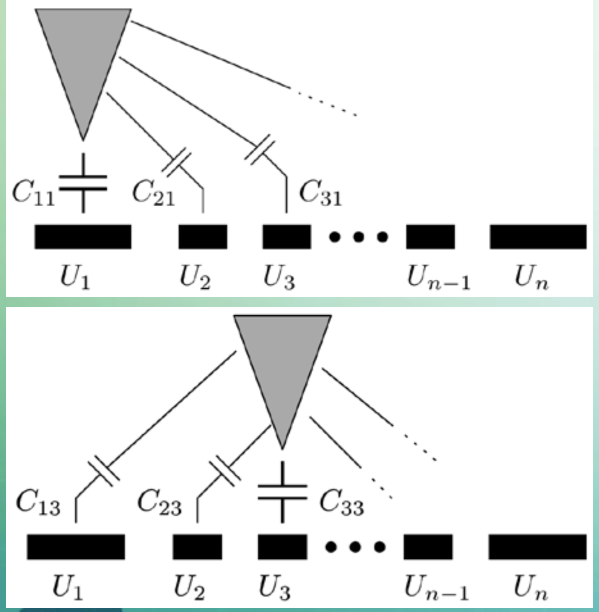
  - Linear capacitance to cone/cantilever (long-range)
  - Constant stray capacitance C_0

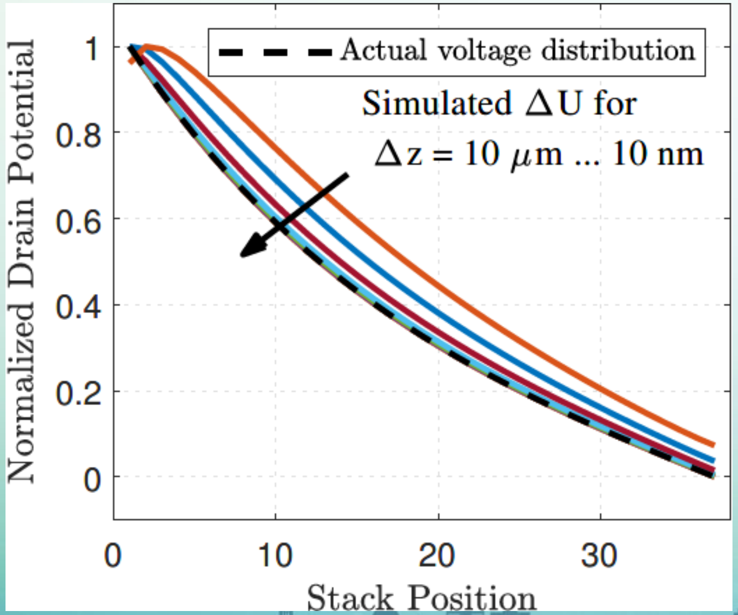


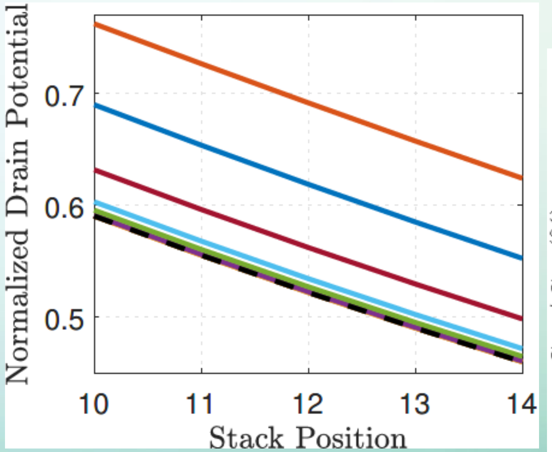


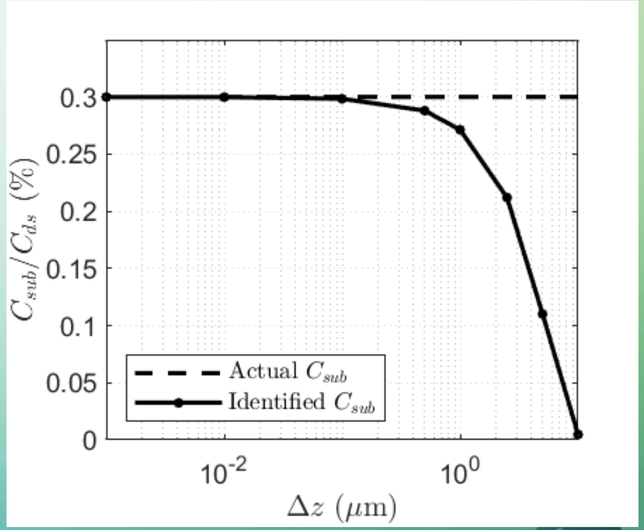
Influence of crosstalk

- Assumption: given voltage distribution in RF switch ($C_{sub}/C_{off} \stackrel{\text{def}}{=} 0.3$ %)
- Previously identifed C(z) used to simulate measured distribution
- Coupling capacitances to adjacent test points based on long-range linear capacitance and known dimensions of switch
- Measurements at ~Δz < 1µm for deviation < 1.5 %



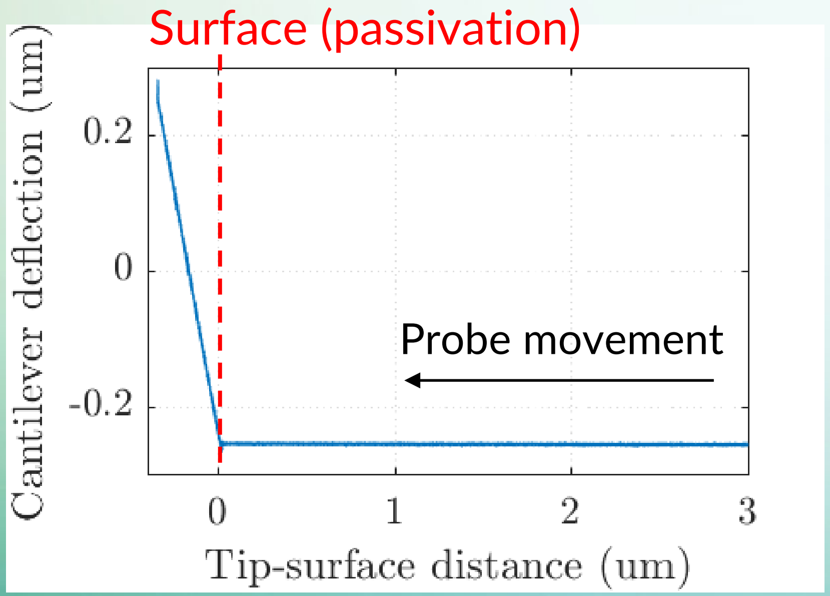


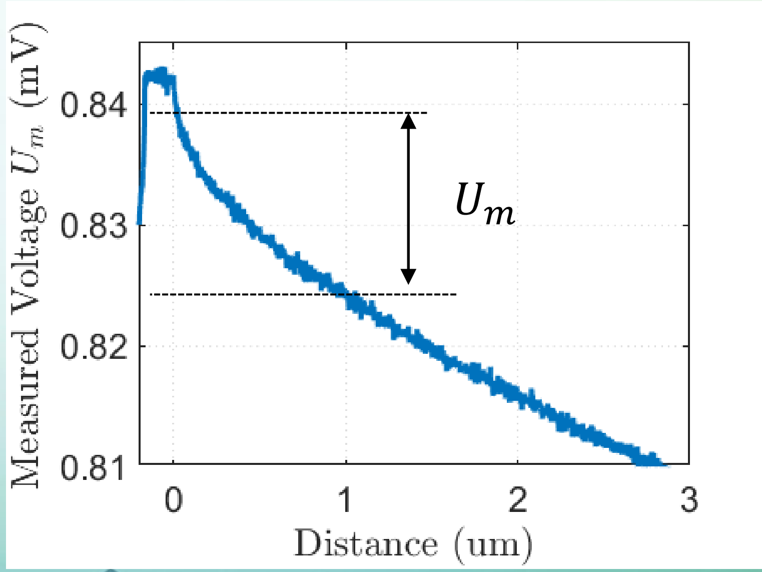




Measurement procedure

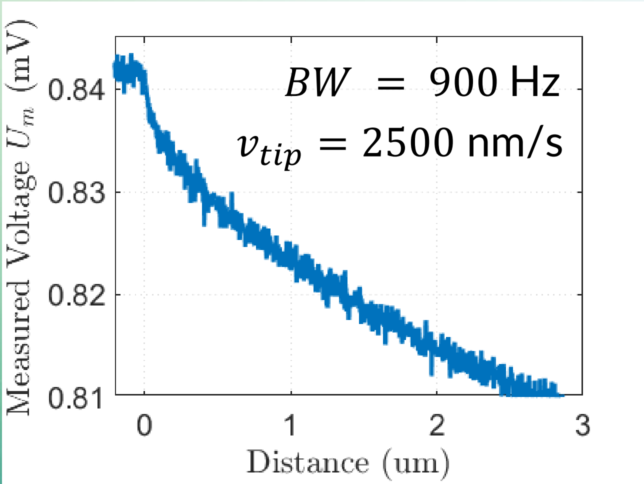
- At each test point: ramp signal applied to z-piezo
- Measurement of cantilever deflection, piezo position and S_{21} during tip-surface approach
- Calculate differential signal at arbitrary distances

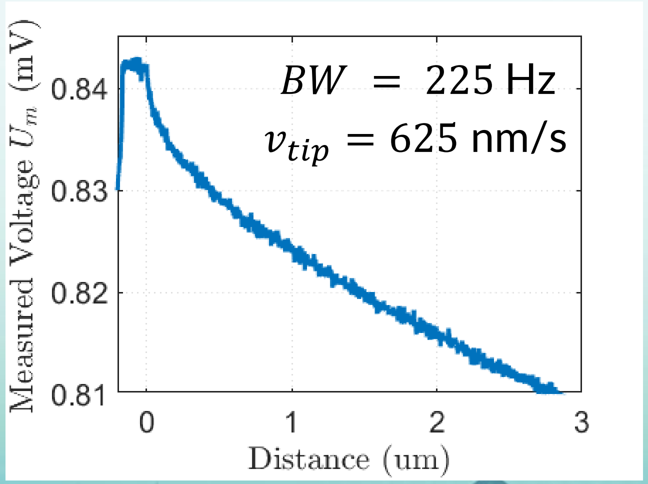


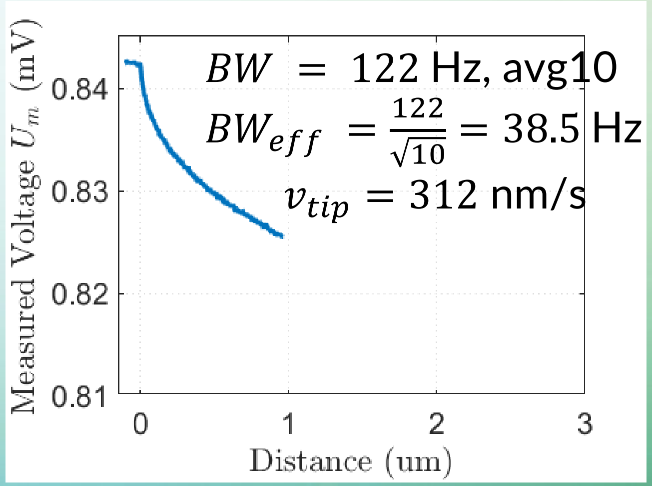


Estimated voltage resolution

- Tradeoff between spatial resolution /crosstalk ($\Delta z \downarrow$) and voltage resolution / sensitivity ($\Delta z \uparrow$)
- SNR = 114 for BW_{eff} 38.5 Hz, U = 1 Vpk (10 dBm) and Δz = 1 µm
- Minimum detectable signal (SNR = 2): 3 mVpk (-40 dBm)
- Measurement duration ~30 s

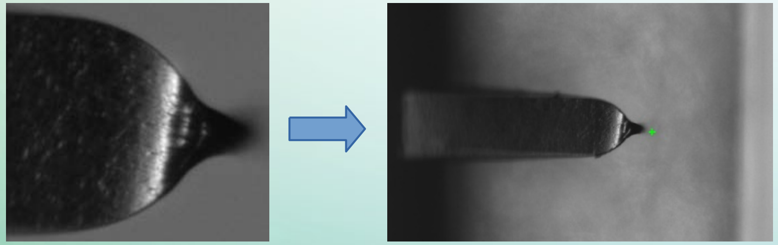


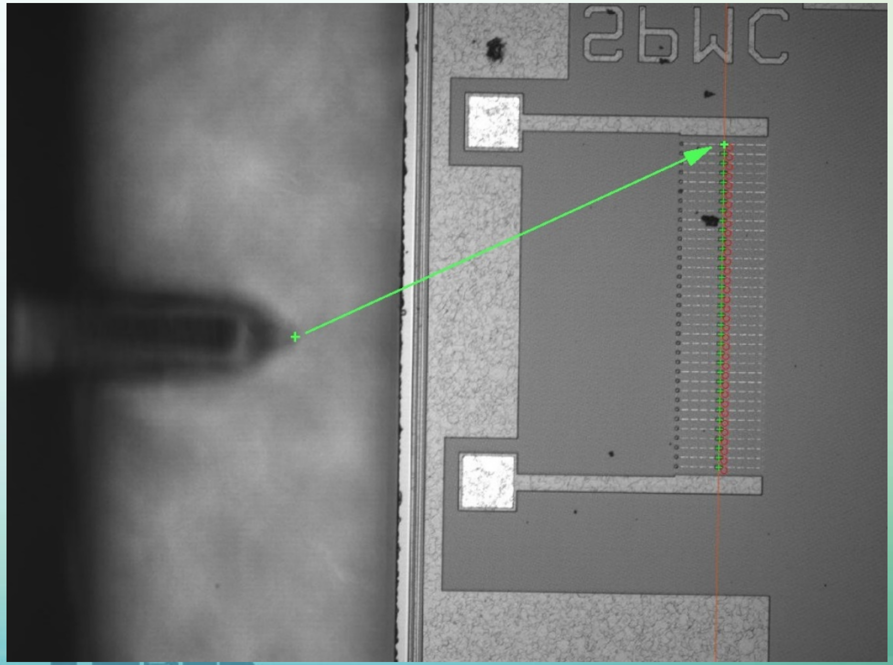




Tip-circuit alignment

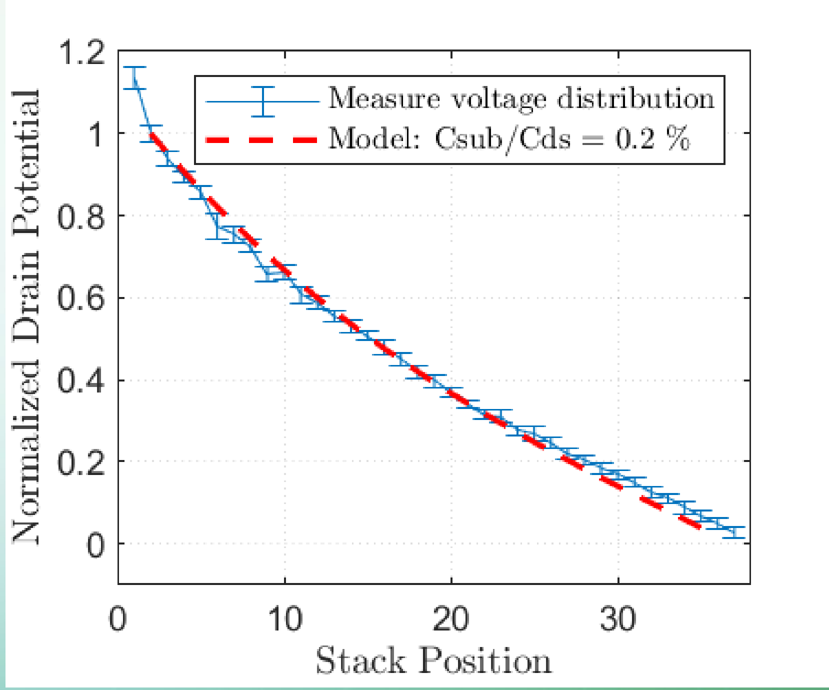
- Manual movement to first test point and subsequent automated movement based on known layout - only if tip is visible, limited repeatability
- Vision-based probe tip and test point detection
- Automated movement to identified locations with sub-um repeatability





Results

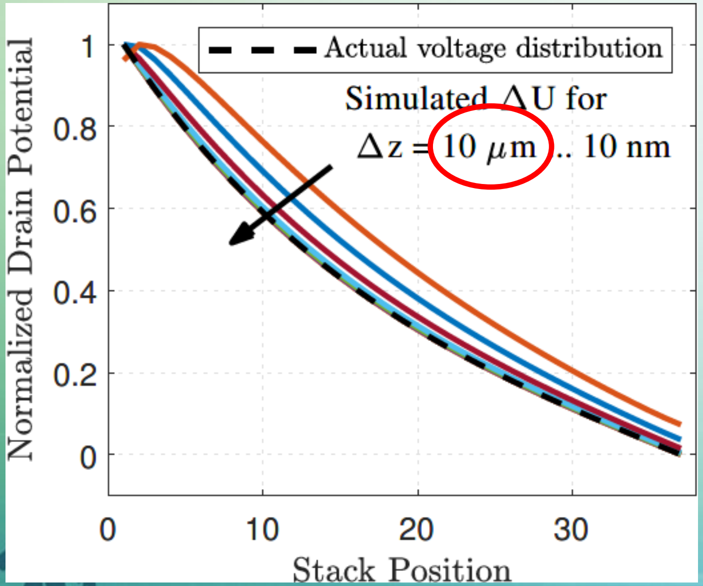
- RF signal of P = 10 dBm and 1 GHz applied to RF switch
- Distances between measurements: $\Delta z = 0.1\ \mu\mathrm{m}$
- Measured voltage distribution
  - Reasonable result, close to simplified model with $C_{sub}/C_{off} \approx 0.2\ \%$
  - Large value at first drain electrode probably artifact due to larger size
  - Normalized to second drain electrode (assuming stacked switch with 35 FETs)



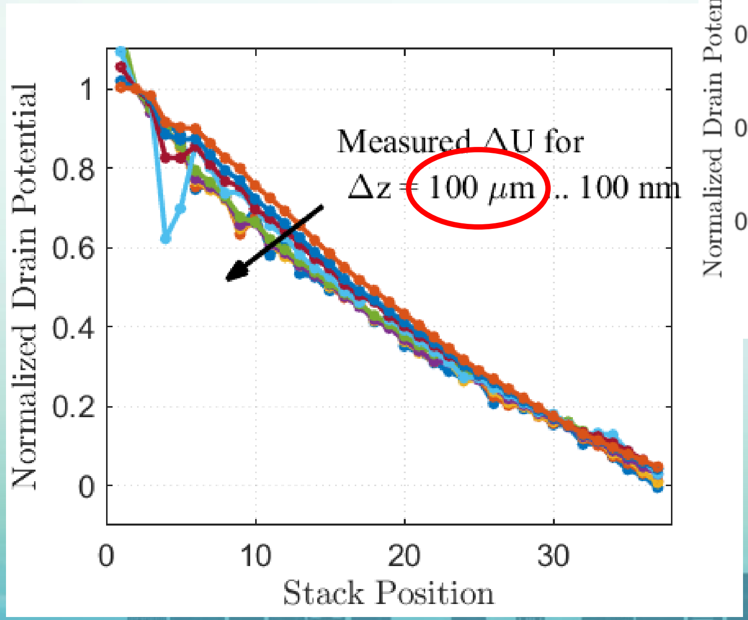
Results - crosstalk

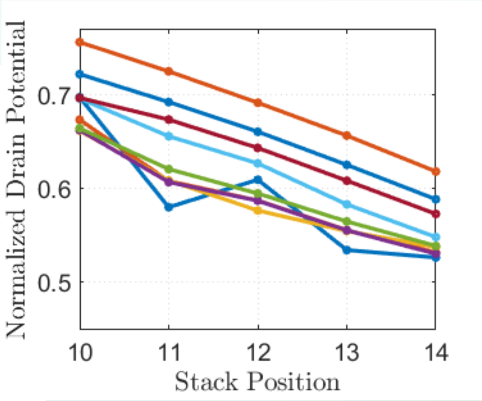
- Distances between measurements: $\Delta z = 0.1 \ldots 100\ \mu m$
- Influence of crosstalk smaller than expected by simulation
- Long-range linear C(z) in simulation probably overestimates crosstalk
- Measured distribution and identified C_{sub} approache constant value for small Δz

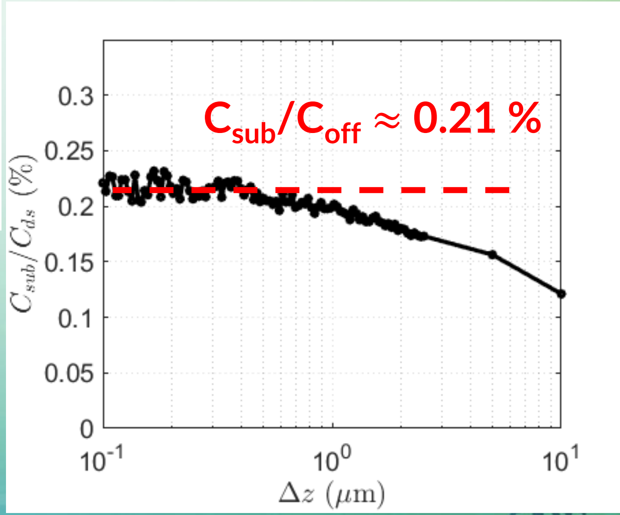
Simulation



Measurement

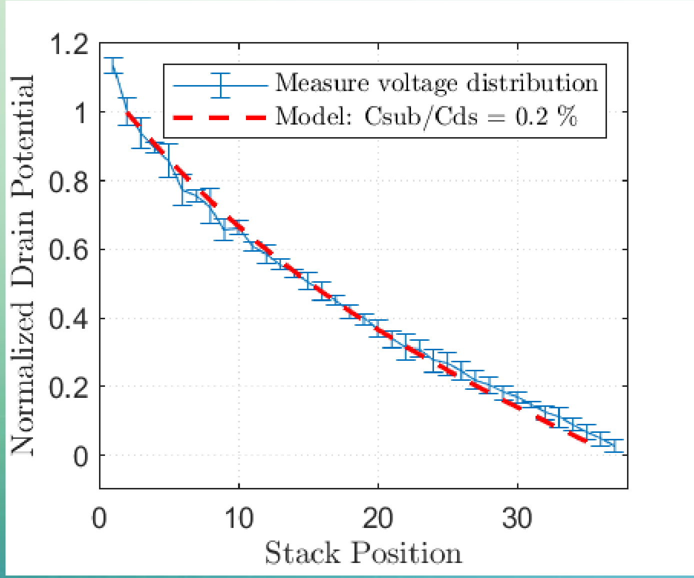


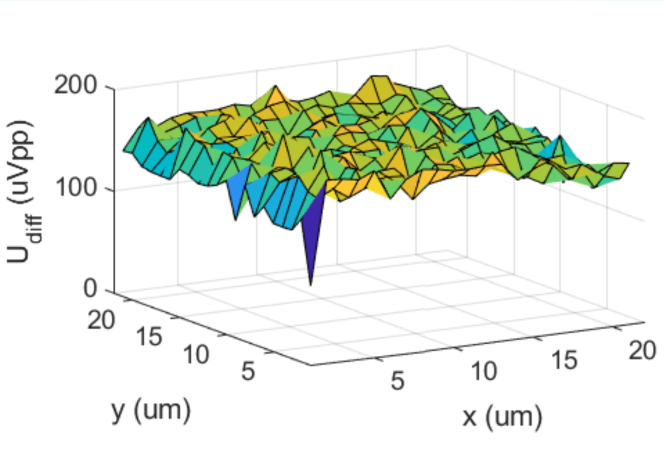


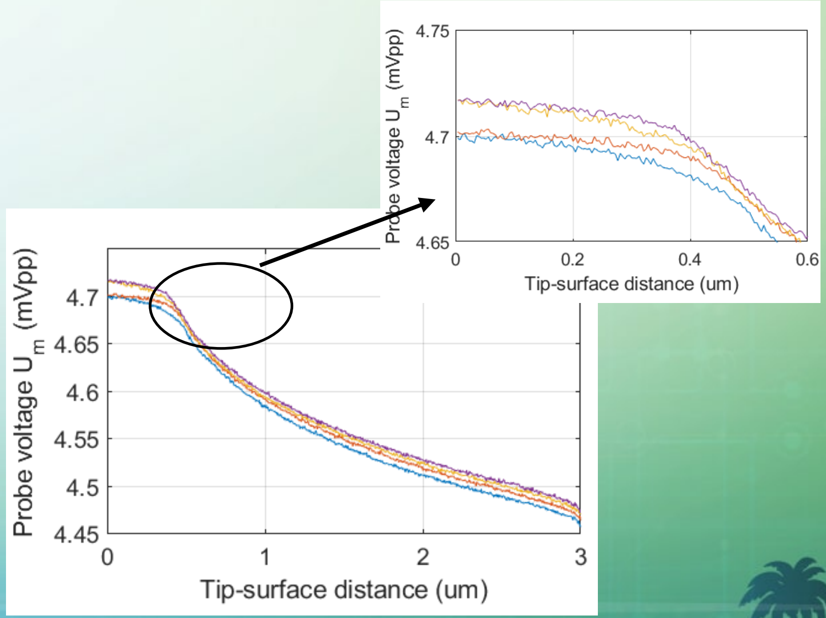


Results – voltage resolution

- Distances between measurements: $\Delta z = 0.1\ \mu\text{m}$
- Errorbars show standard deviations for 10 measurements per electrode
- Voltage resolution of ≈ 20 mV (-24 dBm)
- Surface roughness and difficult detection of tip-surface contact limits repeatability in used measurement procedure

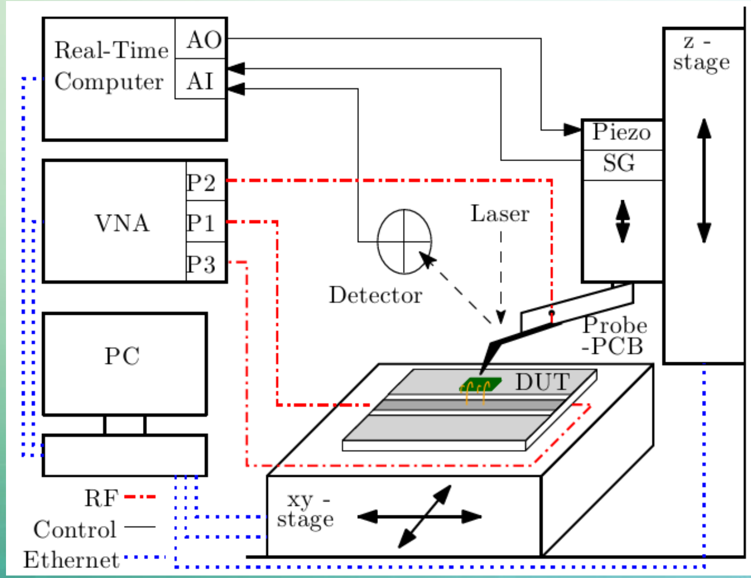


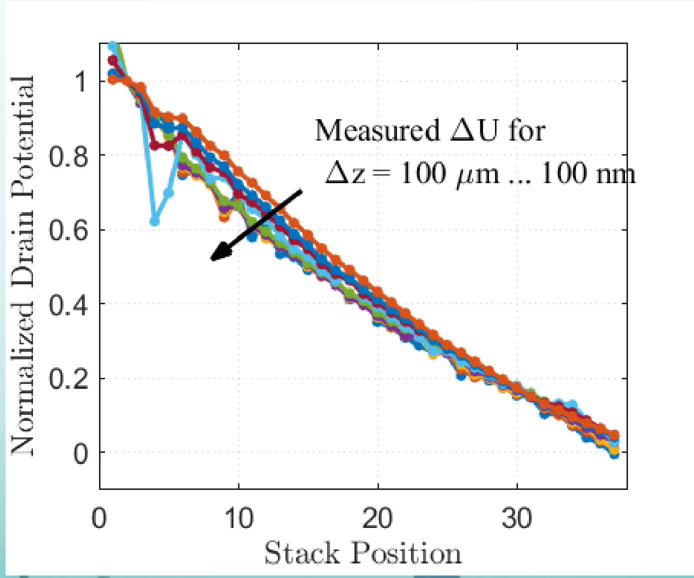


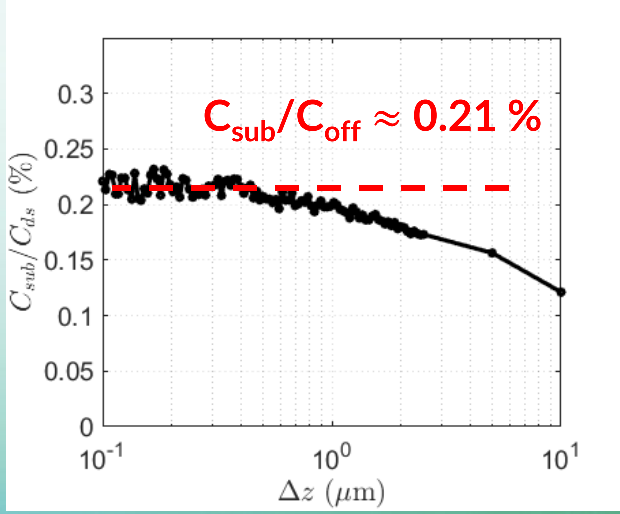


Conclusion

- System for contactless RF measurements implemented
- Feasibility of measuring voltage distributions in RF switches at high spatial resolution demonstrated







Thank You!

- **Questions ?**
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