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

Mathias Poik – ACIN, TU Wien
Sergey Bychikhin - Alten GmbH
Martin Schober – ACIN, TU Wien
Hans-Dieter Wohlmuth – Infineon Technologies
Werner Simbürger - HPPI GmbH
Georg Schitter – ACIN, TU Wien

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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 capability
  → stacked FET switches
Voltage distribution in stack

- Even voltage distribution desired \( \rightarrow \) same voltage drop on each FET
- Uneven voltage distribution due to parasitic effects limits power handling capability and linearity
- Simplified model
  - Off-state capacitance \( C_{\text{off}} = C_{d_s} + C_{g_d} || C_{g_s} \)
  - Parasitic substrate capacitances \( C_{\text{sub}} \)
  - Voltage distribution depending on \( C_{\text{sub}} / C_{\text{off}} \)

Example:
\[
C_{\text{off}} = 1 \text{pF}, \quad C_{\text{sub}} = 1 \ldots 5 \text{fF}
\]

\[
C_{\text{sub}} / C_{\text{off}} = 0.1 \ldots 0.5 \% 
\]
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*
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
\[
\frac{V_m}{V} = \frac{j\omega Z_0 C_{\text{sense}}}{1 + j\omega Z_0 (C_{\text{sense}} + C_g)}
\]

• Differential measurement to reduce crosstalk
\[
\Delta V_m \approx V \cdot \Delta C_{\text{sense}}(z) \cdot j\omega Z_0
\]
Probe selection

- Sharp tip with radius $\ll$ 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 with $n = 36$ identical FETs
- Test points on drain metals for defined coupling capacitance
- Test point size: $2.4 \times 8 \, \mu m$
- Distance of $10 \, \mu m$ between test points
- Passivated surface ($\sim 1 \, \mu m$ 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 ($C_{\text{sub}}/C_{\text{off}} \equiv 0.3\%$)
- Previously identified $C(z)$ used to simulate measured distribution
- Coupling capacitances to adjacent test points based on long-range linear capacitance and known dimensions of switch
- Measurements at $\Delta z < 1\mu m$ for deviation $< 1.5\%$
Measurement procedure

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

![Graph of Cantilever deflection and Measured Voltage](image)
Estimated voltage resolution

- Tradeoff between spatial resolution / crosstalk ($\Delta z \downarrow$) and voltage resolution / sensitivity ($\Delta z \uparrow$)
- SNR = 114 for $BW_{\text{eff}}$ 38.5 Hz, $U = 1$ Vpk (10 dBm) and $\Delta z = 1 \mu$m
- 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: $\Delta z = 0.1 \, \mu m$
- 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: $\Delta z = 0.1 \ldots 100 \, \mu\text{m}$
- Influence of crosstalk smaller than expected by simulation
- Long-range linear $C(z)$ in simulation probably overestimates crosstalk
- Measured distribution and identified $C_{\text{sub}}$ approach a constant value for small $\Delta z$

Simulation Measurement

$C_{\text{sub}} / C_{\text{off}} \approx 0.21 \%$
Results – voltage resolution

- Distances between measurements: $\Delta z = 0.1 \, \mu m$
- Errorbars show standard deviations for 10 measurements per electrode
- Voltage resolution of $\approx 20 \, mV \, (-24 \, dBm)$
- 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

\[ \frac{C_{\text{sub}}}{C_{\text{off}}} \approx 0.21\% \]
Thank You!

- Questions ?
- Contact:
  - Mathias Poik
    poik@acin.tuwien.ac.at
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