Summary

We present a novel, fast, and cost-effective method to measure the capacitance-voltage relation of an electronic device. Capacitances are determined using a single-frequency 1-port S-parameter setup constructed from discrete components. A new way is introduced to correct for non-linearities of the used components. C-V curves are measured in less than a millisecond, with measurement accuracy well below 1%. The technique is validated on an RF-MEMS capacitive switch and a BST tunable capacitor.
Fast RF-CV Characterization Through High-Speed 1-port S-parameter Measurements

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Abstract—We present a novel method to measure the capacitance-voltage relation of an electronic device. The approach is accurate, very fast, and cost-effective compared to the existing off-the-shelf solutions. Capacitances are determined using a single-frequency 1-port S-parameter setup constructed from discrete components. We introduce a new way to correct for non-linearities of the used components, which greatly increases the accuracy with which the phase and magnitude of the reflected signal is measured. The measurement technique is validated on an RF-MEMS capacitive switch and a BST tunable capacitor. Complete capacitance-voltage curves are measured in less than a millisecond, with a measurement accuracy well below 1%.

I. INTRODUCTION

Capacitance-Voltage (C-V) measurements are essential for the electrical characterization of electronic devices [1]. In particular, for MOS transistors, tunable capacitors (e.g. varactors) and RF-MEMS capacitive switches this type of measurement enables the direct extraction of principal electrical performance parameters.

Accurate C-V measurements however are not easy to carry out. The instrumentation is non-trivial: the cables, wafer chuck, measurement instruments all are non-ideal and thereby introduce errors. In most cases the components themselves are also non-ideal, asking for careful correction of parasitics. Such parasitics further may lead to high dissipation, resulting in a loss of C-V measurement accuracy.

Current trends in C-V measurement are improvements in instrumentation (e.g. Keithley 4200), raising frequencies (e.g. Agilent E4991A), changing test structure designs, and increasing throughput. By improving instrumentation, the C-V measurement becomes less error-prone and yields more accurate results. Raising the measurement frequency has the benefit of being less sensitive to parallel leakage currents, as eminent in modern CMOS transistors. However test structure design then becomes more critical (see e.g. [2]).

For CMOS, RF-CV [3], or more precisely, C-V measured at 10-1000 MHz, is becoming the de-facto standard. This approach combines high frequency impedance measurement (using LCR meters or Vector Network Analyzers (VNAs)), RF probing, and calibration and de-embedding of some sort. The measurement is complex to set up, but once operational it can be performed in a few minutes.

In this paper we present a different instrumental approach, offering much faster single-frequency C-V measurement at lower cost. A higher measurement speed can lower the testing cost, but also brings more generic advantages, such as the reduction of measurement-implied stress (see e.g. [4], [5]).

The technique makes use of a single-frequency 1-port VNA with extremely high baseband bandwidth. It is based on work by Nieminen et al. [6]. In this paper we analyze the measurement accuracy and show how it can be greatly improved by a good selection of hardware and by introducing a new calibration technique with which the significant non-linearities of the used components can be corrected. Further, we validate the technique on two emerging RF components.

II. HARDWARE

In the system we introduce here, capacitances are determined by measuring the reflection-coefficient of a DUT essentially with a single frequency 1-port VNA. The system is based on the description given by Nieminen et al. [6], and is schematically depicted in Fig. 1.

It works as follows: an RF signal provided by a Rohde&Schwarz SML03 RF Signal generator travels to a splitter (Mini-Circuits 15542 ZC3PD-900). One part of the signal goes into the local oscillator of the IQ-demodulator, a Mini-Circuits ZAMIQ-895D. The other part passes through a circulator (Ditom D3C0890) to a bias-T selected for its fast response to dc input changes. This bias-T is a combination of a 100 pF capacitor, 1 kΩ resistor, and a small capacitor to ground.

The signal then reflects back from the device under test. It passes through the capacitor of the bias-T, after which the circulator passes the signal to the RF-in port of the IQ-demodulator. The IQ-demodulator mixes the signal at the RF-in port with the LO port for the In-phase part (I) and also mixes it with a 90° phase shifted LO for the Quadrature phase part (Q). The voltage at the I and Q port are measured using an NI PCI5105 data acquisition card. This card has combines a high sampling rate (up to 60 million samples per second) with a high (12-bit) digitizer accuracy. The 10-dB attenuator (Fig. 1) reduces the test signal to stay within the most linear region of the IQ-demodulator.
The calibration of this measurement system is detailed in the following two subsections.

A. Calibration of the IQ-demodulator

The IQ-demodulator is calibrated using the setup shown in Fig. 2. RF1 is the RF Signal generator connected to the Local Oscillator (LO) port of the IQ-demodulator and provides an 890 MHz signal at a constant RF power level. Reference signal RF2 is provided by a second signal generator (locked to the same reference clock), and is detuned 1 kHz relative to RF1, so that at port I and Q there is a 1 kHz sine- and cosine-like signal. The 1 kHz square wave provided by a function generator is for triggering purposes.

Ideally, when the I and Q signal are converted to polar coordinates, $r$ should be a constant when the RF voltage is held constant, and $\phi$ should linearly increase with time. In reality, the measured $r$ and $\phi$ will deviate from this (i.e. $r_{\text{measured}}$ and $\phi_{\text{measured}}$ are an unknown function of $r_{\text{applied}}$ and $\phi_{\text{applied}}$), but in a reproducible manner.

Fig. 3 shows a set of measured RF amplitudes and phase deviations as a function of applied amplitude and phase. A clear and systematic phase dependence exists in the measured RF amplitude, especially at higher applied RF voltages. More important for capacitance measurements is the relatively large phase deviation: even for the situation least sensitive to phase errors (high RF amplitude), the phase error has a maximum of more than 30 mrad. As the errors depend on amplitude and phase, a standard Open-Short-Load calibration does not suffice to eliminate them. However the errors are systematic and rather constant in time, so once quantified they are easily corrected for.

The data set of Fig. 3 is used to construct a lookup table, with which we map measured, distorted, RF signals to much more accurate calibrated values (using a straightforward, linear interpolation technique). Note that with the above outlined method for obtaining the lookup table, mapping and interpolation should be done in polar coordinates, otherwise the magnitude of a reflected signal will be underestimated.

As can be seen in Fig. 4, using the calibration greatly reduces errors. Note that different RF levels are used, to check if signals which are not close to one of the points in the lookup table are correctly mapped. Closer examination of the data showed that (r.m.s.) measurement errors are reduced to 0.25% on the amplitude, and to 0.32 mrad on the phase. Further details on the implementation of the correction approach may be found in [7].

B. Calibration of cables and other passives

After this calibration the setup can accurately measure phase and magnitude of a reflected signal. However, since the setup is essentially a 1-port single frequency VNA, the combined effect

![Fig. 5. Schematic showing how phase shifts and losses due to cables, RF probe, and other passive components can be modelled.](image-url)
of internal reflections and losses in cables, the RF probe, and other passive components must be known in order to calculate the reflection coefficient of a device under test. This can be described as a 2-port error box [8]–[10]. See also Fig. 5. In the figure \( a_1 \) and \( a_2 \) are the incoming waves at ports 1 and 2, \( b_1 \) and \( b_2 \) the waves travelling away from ports 1 and 2. Port 1 is connected to the test setup. The relation between incoming and outgoing waves can be described as:

\[
\begin{bmatrix}
  b_1 \\
  b_2 \\
\end{bmatrix} = S \begin{bmatrix}
  a_1 \\
  a_2 \\
\end{bmatrix}.
\]

The measured reflection coefficient \( \Gamma_M \) depends on error matrix \( S \) and the DUT’s reflection coefficient \( \Gamma_A \) as [9]

\[
\Gamma_M = \frac{b_1}{a_1} = S_{11} + \frac{\Gamma_A S_{12} S_{21}}{1 - \Gamma_A S_{22}}.
\]

To calculate \( \Gamma_A \), we need to know \( S_{11}, S_{22} \) and the product \( S_{12}S_{21} \). To determine these three unknowns, \( b_1/a_1 \) is measured for three different \( \Gamma \)’s: an open, short and 50-\( \Omega \) load on a calibration substrate. \( \Gamma_A \) can then be found from \( S_{11}, S_{22}, \) and \( S_{12}S_{21} \) by inverting Eq. 2:

\[
\Gamma_A = \frac{\Gamma_M - S_{11}}{(\Gamma_M - S_{11}) S_{22} + S_{12} S_{21}}.
\]

From this the impedance can be calculated [11] using:

\[
Z = 50 \left( \frac{\Gamma + 1}{\Gamma - 1} \right).
\]

III. RESULTS

We compared the new setup to a HP 8753C VNA calibrated at 890 MHz with the same calibration substrate. We first measured and compared 5 fixed capacitors between 0.2 and 58 pF with both setups. The amplitude difference was on average –0.8% and had a standard deviation of 2%, while the phase difference was on average 0.8 mrad and had a standard deviation of 4 mrad. For a large part these differences were caused by drifting of the Fast RF-CV setup due to fluctuations in the ambient conditions. Over a capacitance range of 100 fF to 100 pF this results in an overall error in capacitance measurement of less than 7% (see Fig. 6, also showing similar curves for other test frequencies). The best accuracy naturally occurs at \((\omega C)^{-1} = 50 \, \Omega\), where the (one sigma) error margin is only 0.4%.

The same instruments were used to characterize an RF MEMS capacitive switch; see Fig. 7. Only a slight discrepancy is observed in the location of the right-most location sudden change in capacitance (positive pull-in voltage). This could be attributed to the fact that we used two different function generators to provide the voltage, or by a slight degradation of the DUT between measurements.

At sweep rates above 500 V/s, the inertia of the RF-MEMS switch appears in the \( C-V \) characteristic [12]. The pull-in and pull-out voltages are then incorrectly deduced from the measurement. Therefore, Fast RF-CV measurement of this device takes at least 400 ms.

Barium-strontium-titanate (BST) capacitors show a response to bias change faster than 30 ns be it with a few-percent tail decaying in 20 \( \mu \)s [13]. Such capacitors are better suited to test the real speed of our setup. Fig. 8 shows \( C-V \) curves obtained with Fast RF-CV compared with VNA measurements (left). The right-hand figure illustrates that the obtained curve is independent of sweep rate up to 120 V/ms, allowing this curve to be measured correctly within 50 \( \mu \)s.

The match between Fast RF-CV and the VNA measurement in Fig. 8 is not as good as in Fig. 7. This can be explained by the fact that for this device the VNA measurement was done manually. Because of this, the device exhibits more hysteresis during the VNA measurement. This is visible in the VNA.
measurement at around 3.5 V, where the difference between capacitances measured during up-sweep and down-sweep is the largest. As can be seen, at zero volt, where hysteresis is not an issue, there is a good match between VNA and Fast RF-CV.

IV. CONCLUSIONS

We have presented an implementation of Nieminen’s approach for fast capacitance measurements. Measurement accuracy of this method was improved by a careful selection of hardware, and the use of a new way to correct for nonlinearities. The system can be used to measure complete capacitance-voltage curves with high accuracy well within a millisecond. The technique utilizes low-cost instrumentation and requires a limited calibration effort. It is shown to yield satisfactory curves on an RF-MEMS capacitive switch and a BST-based tunable capacitor.

REFERENCES