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# Comparison of Low-Frequency and Microwave Frequency Capacitance Determination Techniques for Mm-Wave Schottky Diodes

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*Abstract*—**The differences of low-frequency (1.0 MHz) and high frequency (3 - 10 GHz) capacitance determination techniques are compared in this work. The low-frequency measurements are direct capacitance measurements performed with an LCR meter and the capacitance determination at microwave frequencies is done by extracting the capacitance from S-parameter measurement results. Several discrete and monolithically integrated Schottky diodes are measured with both techniques and the differences of the techniques are discussed in the view of the obtained results. An evaluation is made on which technique is better suited for building a valid capacitance model for a Schottky diode operating at millimeter wave frequencies.**

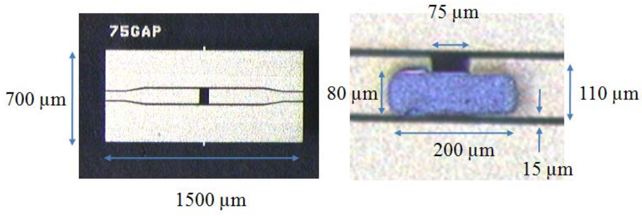
***Keywords-component; Schottky diode, capacitance-voltage, parameter extraction***

## I. INTRODUCTION

The capacitance of a Schottky diode is a parameter of importance for the high frequency performance of the diode as the core element of a mixer, detector, or a frequency multiplier. The Schottky diode capacitance can be divided into the junction capacitance and parasitic capacitance. The junction capacitance and the series resistance create an RC circuit, which limits the highest operating frequency of the diode. A large nonlinear junction capacitance also makes the matching more difficult as the diode impedance becomes dependent on the power of the input or LO signals [1]. A large parasitic capacitance in turn impedes a wideband matching of the device as a large complex conjugate embedding impedance is difficult to realize over a wide bandwidth.

The capacitance of a diode can be determined by a number of ways. One can use theoretical calculations [2], physical simulations [3], 3D electromagnetic modelling [4], [5], low-frequency measurements with an impedance analyzer [6] or with an LCR meter [7], [8] or extraction from microwave measurements [9], [10]. A low-frequency measurement or extraction from microwave measurements yields a value for the total capacitance of the diode. The junction capacitance and parasitic capacitance along with other capacitance-voltage (C-V) parameters are then solved by fitting the results to a nonlinear capacitance equation in a least-squares sense.

In this work the low-frequency measurement technique using an LCR Meter and the capacitance determination from on-wafer S-parameter measurements are compared and the differences of the techniques are discussed based on the measurement results. It is also shown that in the presence of trap states of with monolithically integraged diode the traditional low-frequency determination does not provide reliable results. C-V parameters of several mixer diodes, discrete and monolithically integrated, are determined using both techniques. The monolithic diodes are fabricated using United Monolithic Semiconductors (UMS) BES process. The discrete Schottky diodes are 1MSQ08 from Advanced Compound Semiconductor Technologies (ACST), Darmstadt, Germany and SC2T6 from Virginia Diodes Inc. (VDI), Virginia, USA. To the authors' knowledge this is the first report of a quantitative comparison of low-frequency and microwave frequency capacitance determination techniques for millimeter wave Schottky diodes.



a) b)

Figure 1. Photographs of a) the test mount for discrete diodes and b) diode attached on the test mount.

## II. MEASUREMENTS TECHNIQUES AND C-V PARAMETER EXTRACTION

For the tests, the discrete diodes are attached on coplanar waveguide (CPW) test mounts fabricated on 254 µm thick fused quartz substrate with 3 µm gold-plating. The test mount and a close-up of a mounted discrete diode are shown in Figure 1. The monolithic diodes are embedded in a CPW transmission line center conductor. The substrate thickness is 100 µm. Figure 2. shows a test structure of a monolithically integrated diode with the dimensions.

### *A. Low-Frequency LCR Meter Measurements*

The low-frequency measurements in this work have been performed using Agilent 4284A Precision LCR Meter. The measurement principle is a so-called auto-balancing method, which is usually the method of choice in today's C-V measurements [11]. The measurements are conducted according to [11]. The contact to the test structure is done using phosphor bronze whiskers with a diameter of 25 µm. The measurement frequency is 1 MHz and the ac voltage 50 mV (a compromise between a good signal-to-noise ratio and the highest possible bias voltage). Averaging factor of 16 is used in all measurements and four bias sweeps are conducted for one connection of the whiskers.

For the discrete diodes the removal of the test mount and whisker parasitic capacitance is done by measuring an empty test mount and reducing that capacitance from the capacitance measurement of the diode on the test mount. For the monolithic diodes the calibration is done using three different methods: 1. lifting one of the whiskers in air and measuring the open-ended capacitance, 2. lifting both whiskers and measuring the open-ended capacitance, and 3. measuring the capacitance of a gap which is fabricated on a monolithic test structure (as Fig. 2 but without the tapered part). The last method is essentially the same as used with the discrete diodes.

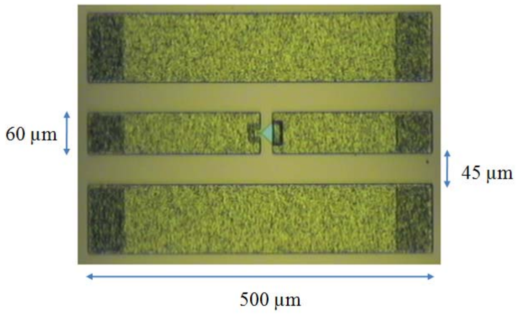


Figure 2. Photograph of the CPW test structure with a monolithically integrated diode (UMS).

### *B. Total Capacitance Determination from S-parameter Measurement Results*

At lower microwave frequencies and in the bias voltage range, where the diode is not yet conducting, the equivalent circuit of the diode can be reduced to pi-network of a series capacitor, $C_T$, and small capacitances from pad edges to the ground, $C_{g1}$ and $C_{g2}$. This is shown in Figure 3. The total capacitance, $C_T$, is the sum of the junction capacitance, $C_j$, and the parasitic capacitance, $C_p$. The magnitude of the transmission coefficient is dependent only on the value of the total capacitance. By fitting the measured value of the transmission coefficient to a calculated value, an accurate estimate for the total capacitance can be extracted. The S-parameters are measured with an Agilent N5250 PNA. The RF power level is kept under -25 dBm at all times. The contact to the CPW pads is done with on-wafer probes. Before the measurements, the system is calibrated using a Cascade Microtech line-reflect-reflect-match (LRRM) calibration kit.

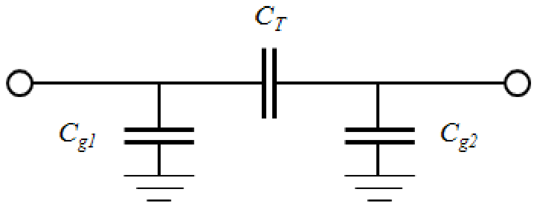


Figure 3. Equivalent circuit for discrete Schottky diode on a test carrier or monolithic Schottky diode. The equivalent circuit is valid when frequency is not too high and the current throught the diode is negligible.

The frequency range where the extraction is done must fulfill two conditions. First, the frequency should be high enough in order to have the transmission coefficient value that is significantly above that caused by the leakage resistance. Second, the frequency should be low enough for the reduction of the equivalent circuit of the diode to the circuit in Figure 3 to be valid. The S-parameters were measured between 0.1 – 110 GHz, but the frequency range of 3 – 10 GHz is used for the capacitance extraction as it fulfills the above criteria.

### *C. C-V Parameter Extraction*

In order to get values for the junction and parasitic capacitances, the total capacitance values are fitted to the nonlinear capacitance equation [1]

$$C_T = C_j + C_p = \frac{C_{j0}}{\left(1-\frac{V}{V_{bi}}\right)^{\frac{1}{2}}} + C_p, \qquad (1)$$

where $C_{j0}$ is the zero bias junction capacitance, $V$ is the applied voltage, and $V_{bi}$ is the built-in voltage. The measurements are done in the bias voltage range of -3 - +0.5 V but in the extraction, all the measurement points cannot be used for monolithic diodes because above 0.4 V the LCR Meter results are unstable as the monolithic diodes start conducting at lower bias voltages than the discrete diodes.

## III. MEASUREMENT RESULTS

The measured C-V parameters are summarized in Table I for four monolithically integrated diodes with different anode widths and for two discrete diodes. The total capacitance values as a function of the bias voltage for one discrete and one monolithic diode are shown in Figure 4. and Figure 5. It can be seen in Figure 4. that the capacitance curve of a discrete diode can be similarly determined using either one of the techniques. Extraction gives for the total capacitance of the SC2T6 diode 9.9 fF and 10 fF, extracted from the S-parameters and measured with LCR Meter, respectively. For comparison, the total capacitance given by the manufacturer is 8 – 10 fF. Only one type of discrete diode can be measured using the LCR

TABLE I

CAPACITANCE-VOLTAGE PARAMETERS EXTRACTED FROM LCR METER AND S-PARAMETER MEASUREMENT RESULTS

| **Diode** | $C_{j0}$ (fF)$^{(1)}$ | $C_p$ (fF)$^{(1)}$ | $V_{bi}$ (V)$^{(1)}$ | $C_{j0}$ (fF)$^{(2)}$ | $C_p$ (fF)$^{(2)}$ | $V_{bi}$ (V)$^{(2)}$ |
|---|---|---|---|---|---|---|
| UMS 3 µm | 1.3 | 25.9 | 0.52 | 1.2 | 12.8 | 0.55 |
| UMS 5 µm | 2.2 | 28.2 | 0.52 | 2.2 | 15.8 | 0.55 |
| UMS 10 µm | 4.7 | 36.2 | 0.52 | 4.8 | 23.4 | 0.55 |
| UMS 20 µm | 9.7 | 51.2 | 0.52 | 10.2 | 39.4 | 0.55 |
| 1MSQ08 | - | - | - | 1.3 | 5.6 | 0.97 |
| SC2T6 | 1.5 | 8.5 | 0.68 | 1.6 | 8.3 | 0.78 |

$^{(1)}$ Extracted from LCR meter measurement results, calibration is done by lifting one of the whiskers

$^{(2)}$Extracted from S-parameter measurement results

Meter. For the 1MSQ08 diode, the measurement results across the frequency and signal amplitude range are always unstable. The reason for this is not fully understood, but it is assumed to be caused by interface trap states in the AlGaAs membrane substrate with such short relaxation times that the traps affect the measurement results even at the highest possible measurement frequency of the LCR Meter (1 MHz). According to the manufacturer, the next generation model of the diode, in which the AlGaAs membrane substrate is replaced by transferred dielectric membrane, shows no such problems. However, the C-V parameters of 1MSQ08 diode can easily be extracted from the S-parameter measurement results as the frequency is so high that the substrate traps have no time to react on the microwave signal. In addition, with the S-parameter technique the capacitance is extracted at a frequency which is much closer to a real application than the LRC Meter measurement, taking into account other possible high frequency phenomena.

It can be seen in Figure 4. that the capacitance curve of a SC2T6 diode can be similarly determined using either one of the techniques. However, this is not the case in the measurement of monolithically integrated diodes. By comparing the results in Table I and the capacitance curves in Figure 5. it can be seen that the extracted values for the junction capacitance and for the built-in voltage are similar regardless of the used technique. However, a significant problem in the capacitance determination of monolithic diodes with an LCR Meter is that the parasitic capacitance of the test structure cannot be fully separated from the parasitic capacitance of the diode. Consequently, the parasitic capacitance extracted from the LCR meter measurements depends largely on how the external capacitance is calibrated out.

If the calibration is done by lifting both whiskers in the air, the calibration does not take into account the capacitance between the two metal plates that are the CPW center conductors. The result is that the extracted parasitic capacitance of the diode is very large. The same applies on the second calibration technique, which is used for the values in Table I. Only in this case the capacitance of one of the pads is not taken into account. This results in a too large value of the parasitic capacitance, but still smaller than in the first case. The third option is to fabricate and measure an empty gap with the same dimensions as in the test structure with the diode and then subtract this from the capacitance measurement of the diode test structure. However, this calibration method underestimates the parasitic capacitance of the diode (seen by the microwave signal) as the fringing capacitance of the gap edges is a significant contributor in the total capacitance and it is now subtracted. The resulting parasitic capacitance for our monolithic diodes is ~5 fF smaller than the value extracted from S-parameter measurements. This effect is not significant in the calibration of the test mount with the discrete diode, as the gap in the test mount is much larger and the substrate is of relatively low permittivity material (fused quartz, $\varepsilon_r = 3.8$).

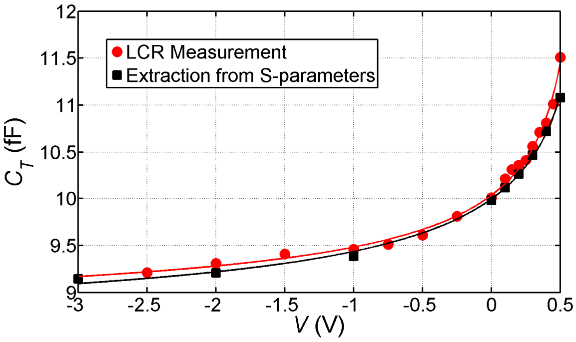


Figure 4. Measured and extracted total capacitances of a SC2T6 diode. The solid lines show the fitted capacitance curves and the dots and squares the measured and extracted values, respectively.

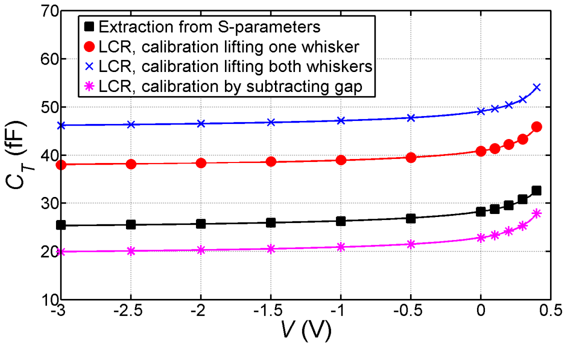


Figure 5. Measured and extracted total capacitances of a UMS 10 µm diode. The total capacitance in the LCR measurements depends on the method how the external capacitance of the test mount is calibrated out

## IV. DISCUSSION ON THE RESULTS

It is shown that in the case of monolithic diodes, the extraction from S-parameter measurement results is better suited for the determination of the parasitic capacitance than the measurement with an LCR Meter. The accuracy of the capacitance extracted from S-parameter measurement results relies on the assumption, that the diode can be modeled as in Figure 3. It is clear that in an ideal diode, the lower the frequency the better the assumption that a diode can be modeled with a single capacitor. However, for real diodes and at sufficiently low frequencies, this assumption is not valid as the leakage current of the diode and/or the measurement system is larger or of the same order as the magnitude of the transmission coefficient.

On the other hand, it is well known, that at high microwave and millimeter wave frequencies the diode cannot be modeled as a single component, but rather using an equivalent circuit consisting (in addition to capacitances) of at least transmission lines for the diode pads, an anode finger inductance, and a series resistance. However, between low and high frequencies, there is a frequency range, where a single capacitor is an excellent model for a discrete or monolithic Schottky diode. For the diodes used in this work, it is observed that the effect of the leakage current is negligible above 2 GHz and that the equivalent circuit model should be used instead of a single capacitor above 15 GHz. In order to maintain a safety margin, the extraction is done between 3-10 GHz. In this frequency range, the capacitance values extracted at discrete frequency points differ less than 0.5 % from the value that is extracted using the full frequency range.

The measured transmission coefficient of the diode and the calculated transmission coefficient of the capacitor with the extracted value of 28.2 fF are shown in Figure 6. It can be seen that the diode can be extremely accurately modeled with a capacitor in this frequency range.

## V. CONCLUSIONS

In this paper we have compared the capacitance determination techniques based on LCR Meter measurements and on the extraction from S-parameter measurement results. We have showed that for discrete diodes, both techniques yield similar results. However, in the LCR Meter measurements of monolithically integrated diodes, the effect of the capacitance of the test structure cannot be fully separated from the effect of the parasitic capacitance of the diode. In this case, the capacitance determination should be done using S-parameter measurement results in order to get as accurate model as possible for the microwave or millimeter wave performance of the diode. Another case where the S-parameter measurement results should be used for the extraction of the capacitance is when the trapping effects disturb the measurements with an LCR Meter. To the authors' knowledge this is the first report of a quantitative comparison of low-frequency and microwave frequency capacitance determination techniques for millimeter wave Schottky diodes.

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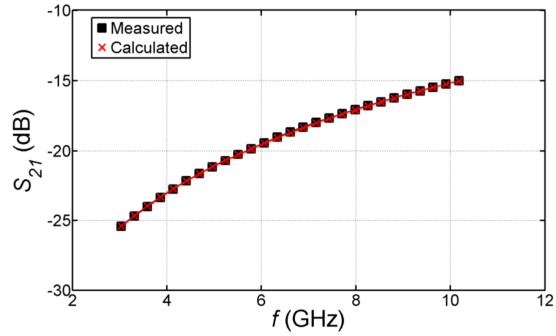

Figure 6. Measured transmission coefficient for the UMS 10 μm diode and calculated transmission coefficient for a 28.2 fF capacitor.

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