Contactless probing of high-frequency electrical signals with scanning probe microscopy

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Abstract — **Circuit internal test techniques working in a contactless manner are necessary for failure analysis and design verification of high-speed and high-frequency circuits. A relative new technique is the Scanning Probe Voltage Measurement technique, a technique which is based on scanning probe microscopy. This paper gives an overview of the state-of-the-art of this technique and demonstrates some practical examples.**

I. Introduction

Studying the latest Semiconductor Industry Association Roadmap, digital integrated circuits (IC) will experience a continual progress in minimizing structure size, increasing operation speed/bandwidth, and reducing power consumption [1]. Not only digital circuits but also high frequency analog circuits (monolithic microwave integrated circuits, MMIC) show a progress in miniaturization, complexity, working frequency, and bandwidth. Modern microwave transistors have extrapolated cutoff frequencies of up to 340 GHz and make possible MMICs with working frequencies up to 213 GHz [2]. It is accepted that at-speed wafer probing is essential for a complete electrical function test of digital IC. Furthermore, it has been shown that beside the electrical function test circuit internal test techniques are necessary for failure analysis and design verification for both high-speed ICs and MMICs [3, 4].

The consequence from this is the development of contactless test techniques [5, 6], which meet the requirements of high spatial resolution, high temporal resolution respectively high bandwidth, and high voltage resolution.

This paper will give a survey of a technique, which is based on scanning probe microscopy: the Scanning Probe Voltage Measurement technique. The principle of this test technique will be introduced followed by a discussion of its state-of-the-art and its limits with the focus on gigahertz applications. Also some examples of applications will be given.

II. Scanning Probe Voltage Measurement Technique

The Scanning Probe Voltage Measurement (SPVM) technique is based on commercially available scanning force microscopes and does not need special environmental conditions like a vacuum. An usual probe consists of a conductive sharp silicon tip at one end of a conductive cantilever (Fig. 1). This probe is scanned at a constant working distance from the device under test (DUT) surface by a xyz-piezoscanner. Due to different distance-dependent tip-DUT interactions the tip is attracted or repulsed from the surface of the DUT. This results in a bending of the cantilever, which is e.g. optically detected and electrically analyzed by a lock-in amplifier giving information of the magnitude and of the phase of the measured signal.

If the distance between the tip and the DUT-surface is within a few nanometers, short-range forces like van der Waals force allow the measurement of the DUT topography with nanometer or even sub-nanometer spatial resolution (non-contact topographic mode) [7].

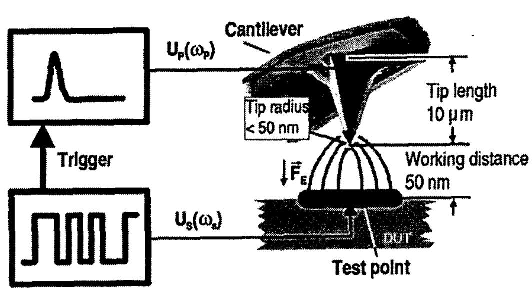

Fig. 1. Principle of Scanning Probe Voltage Measurement Technique

If the probe and the test point are electrically biased and the probe is retracted to a constant height *h* (typically 50 nm) from a test point on the DUT surface, long-range

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forces like the Coulomb force $\vec{F}_E$ become dominant, allowing voltage measurements in the voltage contrast mode. The force and therefore the bending of the conductive probe are now caused by the voltage difference between the probe and the test point. By assuming the capacitor model [8]-[10], the force to the probe can be expressed as

$$F_E = \frac{1}{2}\varepsilon\frac{A}{h}(U_s - U_p)^2 \qquad (1)$$

with $U_S(\omega_S)$ the unknown DUT-internal high frequency voltage signal and $U_P(\omega_P)$ the signal applied to the probe. A is the electrode area and h the working distance. ε is the permittivity of the medium between the probe tip and the DUT-surface. As the cantilever is a mechanical system it shows a low pass behavior with a mechanical resonance frequency up to several tens of kHz. Therefore, the direct measurement of high-speed and high-frequency signals is impossible. However, two principle methods exist for the measurement of fast signals.

A. Mixing technique

If both signals $U_S(\omega_S)$ and $U_P(\omega_P)$ are harmonic signals and recur periodically, the nonlinear dependence between the cantilever bending and the voltage difference $U_S(\omega_S) - U_P(\omega_P)$ produces among other terms a signal component at $\Delta\omega = \omega_S - \omega_P$. Because of the low pass characteristic of the cantilever all terms with frequencies higher than the mechanical resonance of the cantilever are eliminated. If $\Delta\omega$ is chosen as the mechanical resonance of the cantilever high-frequency signals can be measured with a low frequency lock-in amplifier or oscilloscope. This technique is known as the heterodyne mixing technique [11]. Qualitative measurements of sinusoidal electric signals up to 110 GHz have been shown [12]. Another type of mixing technique where the second signal is also fed into the DUT is described in [10] and [13].

B. Sampling technique

For the measurement of periodic non-harmonic signals like digital patterns and especially for quantitative measurements (see below) the voltage applied to the probe is usually an electric pulse generated e. g. by a step-recovery diode (SRD), a nonlinear transmission line, or either by a fast electrical or optical switch. This electrical pulse has to be timely delayed in respect to the signal to be measured which results in the well-known sampling technique. The fastest signal measured with this technique was a 3.2 GBit/s digital pattern [14, 15].

The time resolution resp. the highest measurable frequency component is limited by the temporal width of the sampling pulse and for both techniques it is limited by the possibility of guiding high-frequency signals along the cantilever to the tip. A technique, which overcomes these problems, is discussed in [16].

Because of the uncalibrated relationship between DUT-signal and system output the measurement results are mostly qualitative. By using a suitable control loop it is possible to make the bending of the cantilever zero and to measure quantitatively. With (1) this results in

$$F_E = 0 \Leftrightarrow U_P(t) = U_S(t)\,. \qquad (2)$$

By measuring the free adjustable probe signal U_P the unknown DUT-signal U_S can be achieved quantitatively. This method is known as the zero force method [17, 18]. The quantitative measurement of a 10 MHz broadband signal [18], of a 10 GHz harmonic signal [19], and of a 2 MBit/s signal demonstrates the actual performance [18].

Scanning the probe above distinct device areas and measuring at every point along the scan path allows two-dimensional measurements of the device voltage amplitude. The scan area is approximately 150 µm x 150 µm depending on the used system. Here, bright areas represent high voltage amplitudes and dark areas low voltage amplitudes within the scanned area.

The spatial resolution in the voltage contrast mode is limited by the tip radius of the probe tip and is also influenced by the cross talk of neighboring lines to the probe tip and to the cantilever [20, 21]. For a test structure where the latter could be neglected the spatial resolution was better than 75 nm [22, 23].

The sensitivity is limited by noise induced from the thermal fluctuations of the cantilever or by the fluctuations of the laser beam from the optical detection scheme. The sensitivity is in the order of $1.6\ \mathrm{mV}/\sqrt{\mathrm{Hz}}$. Using averaging techniques this results in a minimum detectable voltage in the order of 5 mV.

III. Measurement of High-Speed Digital Patterns

The following measurements were performed on a passivated conducting line on silicon substrate with 0.5 µm width and spacing. The passivation was 0.7 µm thick. The signal to be measured was a 32 Bit signal (bit combination: 20 Bit low, 4 Bit high, and 4 Bit low) generated by a word generator with a clock rate of 3.2 GHz and amplitude of 3.3 V. A SRD generates a train of 100 ps pulses with 100 MHz repetition rate [15]. The measurement results are shown in Fig. 2.

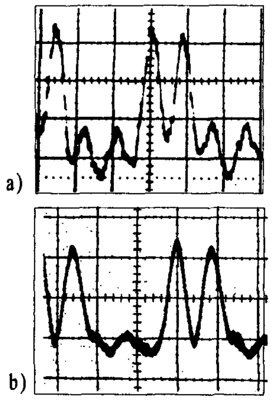

Fig. 2. Measurement of GHz digital signals. a) IC-internal measurement with SPVM. b) Output signal out of the test structure measured with a sampling oscilloscope.

In order to verify the IC-internal SPVM-results (Fig. 2a) circuit external measurements have been done by measuring the output signal of the test structure (Fig. 2b) with a sampling oscilloscope. Apart from a phase shift there is a good correspondence of both signals.

Further examples of SPVM at high-speed digital circuits are given in [14, 15], [18], [24].

IV. Measurement of Microwave Signals

In order to demonstrate the simultaneously achievable high spatial and high temporal resolution of this measurement technique an interdigital structure was driven by a millimeter-wave signal of 1.5 dBm at 105 GHz. A linescan of the voltage magnitude on the finger array (Fig. 3 left side) was performed [25].

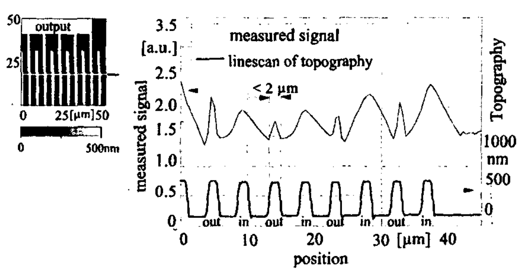

Fig. 3. Linescan of an interdigital structure at 105 GHz with a spatial resolution better than 2 μm.

Fig. 3 shows that the signal differences between the input and the output fingers can be clearly measured.

The following measurements were performed on a 0 - 27 GHz four stage traveling wave amplifier (TWA, Fig. 4) based on InP substrate [26]. Circuit internal measurements were performed on several devices within the TWA [27]. As an example Fig. 4a shows a voltage amplitude map taken at the output line resistor by the SPVM in voltage contrast mode at a frequency of 1 GHz. Due to the geometry of the resistor a linear signal drop towards the ground contact was expected. However, due to a too rapid tapering of the input line of the resistor the voltage amplitude distribution looks different caused by a reflection of parts of the input microwave signal.

Further examples of SPVM at microwave circuits are given in [12, 14], [27]-[29].

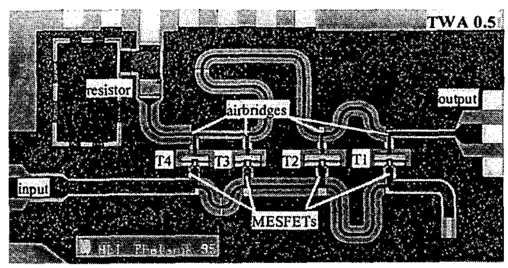

Fig. 4. 4-stage traveling wave amplifier.

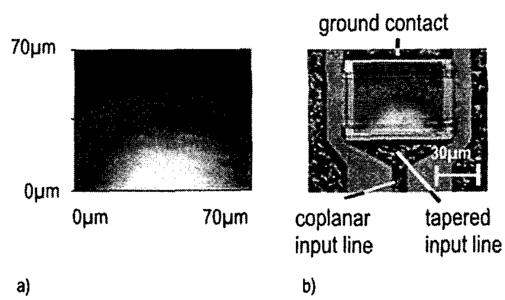

Fig. 5. Measurements at the output line resistor. a) Voltage amplitude map at 1 GHz. b) Topography overlayed by the voltage map.

V. Conclusion

In this paper the Scanning Probe Voltage Measurement technique was discussed regarding its application to high-speed and high-frequency circuits. Measurements of digital patterns up to 3.2 Gbit/s and of harmonic signals up to 105 GHz were demonstrated.

ACKNOWLEDGEMENT

The author would like to thank the DFG and MSWF of NRW for their financial support. Thanks are also given to my co-workers Dr. Böhm, Dr. Leyk, Dr. Wittpahl, and to Dr. Bangert for the measurements and to the Institute of Semiconductor Technique/Technology at the University of Duisburg for the traveling wave amplifier.

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