DESIGN AND CHARACTERIZATION OF INTEGRATED PROBES FOR MILLIMETER WAVE APPLICATIONS IN SCANNING PROBE MICROSCOPY

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ABSTRACT

Scanning probe microscopy has developed to a powerful tool in surface topography and is going to become a characterization method for electrical potentials of monolithic microwave integrated circuits. Measurement bandwidths above 100 GHz force the development of optimized millimeter wave proximal probes with simultaneously nanometer spatial resolution. We present the design, production and characterization of such proximal probes using integrated planar waveguides well suited for the millimeter wave range keeping the nanometer spatial resolution of the tip for topography measurements.

INTRODUCTION

During the last decade the specifications of monolithic microwave integrated circuits (MMICs) have increased dramatically. Forced by a growing communication market, modern MMICs show submicron structures driven with 210 GHz signals [1]. Circuit problems occurring in such complex, large scale integrated, high frequency circuits call for highly accurate measurement techniques with both high temporal and high spatial resolution. Beside the needle probe station, which is less suitable for device internal measurements, electro-optic sampling is well established for MMIC internal measurements but suffers today from limited spatial resolution [2,3]. With regard to the analysis of today's and future MMICs a new contactless test tool with combined very high resolution limits, the electric force tester, has been introduced [4-8]. However, the maximum measurement bandwidth in the voltage contrast mode is limited by the pulse width of the sampling pulse on the probe. For millimeter wave and future submillimeter wave applications this proximal probe has to be optimized as far as possible.

PRINCIPLE OF THE ELECTRIC FORCE TESTER

An electric force tester, based on a scanning force microscope (SFM) for the measurement of electrical potentials utilizes a proximal probe consisting of a sharp conducting tip mounted on one end of a cantilever which is scanned across the surface of a device (Fig. 1). An electrical signal on a transmission line causes locally a deflection of the cantilever due to the Coulomb interaction which is optically detected. As the mechanical response characteristic of the proximal probe precludes the measurement of fast voltage changes a mixing scheme has to be used where the proximal probe is biased with either a sine wave signal or a voltage pulse. In this way, high measurement bandwidths up to 104 GHz and a spatial resolution below 100 nm in the voltage contrast mode have been demonstrated [5,6]. Additionally, nanometer spatial resolution in topography mode is possible [4]. The basic principle of the mixing scheme can be explained using a plate capacitor with spacing h as a simple model for the probe/MMIC arrangement. Assuming a time dependent voltage $U_S(t)$ on the probe and a time dependent voltage $U_P(t)$ on the MMIC a square dependency of the electrical force $\bar{F}$ between the probe and the MMIC (normal to the two plates, y-direction) on the voltage difference $U_{SP}(t) = U_S(t) - U_P(t)$ will occur.

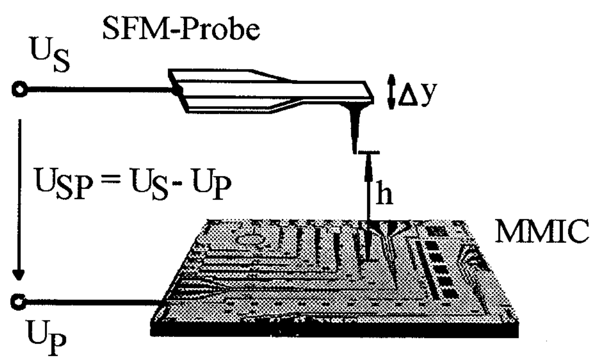

Figure 1: Basic principle of electric force microscopy (plate capacitor model).

The bending of the conductive SFM probe which is in a fixed height h above the sample surface is caused by the voltage difference $U_{SP}(t)$ between the probe voltage $U_S(t)$ and the sample voltage $U_P(t)$. The effective force $\bar{F}$ on the probe depends on the voltage difference and the probe position, leading to

$$\bar{F}(U_{SP},h) = \frac{1}{2}\cdot\varepsilon\cdot\frac{S}{h^2}\cdot(U_S - U_P)^2\cdot\bar{e}_y. \qquad (1)$$

Solving Eq. 1 for the case of high frequency sinusoidal voltages gives:

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$$\bar{F}(U_{SP},h) = \frac{1}{2}\cdot\varepsilon\cdot\frac{S}{h^2}\cdot\Big[\ \frac{1}{2}\cdot\hat{u}_S^{\,2} + \frac{1}{2}\cdot\hat{u}_P^{\,2} - \frac{1}{2}\cdot\hat{u}_S^{\,2}\cdot\cos(2\omega_S\cdot t) - \frac{1}{2}\cdot\hat{u}_P^{\,2}\cdot\cos(2\omega_P\cdot t) + \hat{u}_S\cdot\hat{u}_P\cdot\cos(\omega_S\cdot t+\omega_P\cdot t) - \hat{u}_S\cdot\hat{u}_P\cdot\cos(\omega_S\cdot t-\omega_P\cdot t)\ \Big]\cdot\bar{e}_y. \tag{2}$$

Taking into account that high frequency terms in Eq. 2 ($2\omega_S$, $2\omega_P$, $\omega_S + \omega_P$) are eliminated by the low mechanical bandwidth of the probe Eq. 2 simplifies. This means that the force on the probe depends (beside the two static terms) on a difference term $\omega_S - \omega_P$ modulated with the amplitude $\hat{u}_S$ of the known probe signal and the unknown amplitude $\hat{u}_P$ of the MMIC signal.

$$\bar{F}(U_{SP},h) = \frac{1}{2}\cdot\varepsilon\cdot\frac{S}{h^2}\cdot\Big[\ \frac{1}{2}\cdot\hat{u}_S^{\,2} + \frac{1}{2}\cdot\hat{u}_P^{\,2} - \hat{u}_S\cdot\hat{u}_P\cdot\cos(\omega_S\cdot t-\omega_P\cdot t)\ \Big]\cdot\bar{e}_y. \tag{3}$$

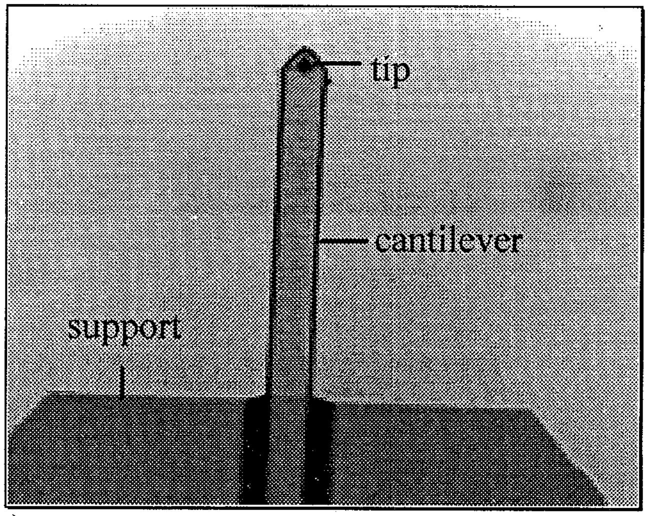
In this way the former high frequency sample signal is down converted to the frequency difference $\omega_S - \omega_P$. If this frequency difference is well below the mechanical resonance frequency of the cantilever the probe movement will directly follow the MMIC signal.

DESIGN OF OPTIMIZED PROBES

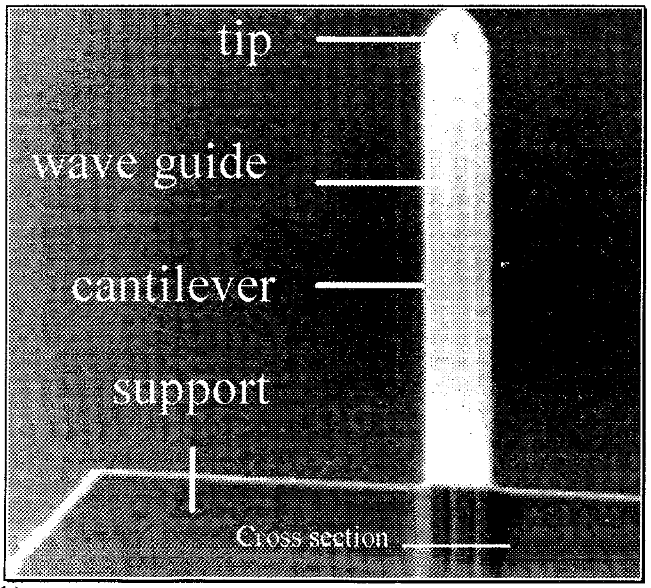
The maximum measurement bandwidth in the voltage contrast mode of an electric force tester is mainly limited by the pulse width of the sampling pulse on the probe. Standard pulse generators produce electrical pulses with amplitudes up to 10 V and a pulse duration of about 130 ps [2]. Further improvements can be made using non-linear devices for pulse compression, like non-linear transmission lines, leading to pulse duration's below 1 ps [8]. Millimeter wave applications support the need for such short electrical pulses and therefore, optimized probes with integrated coplanar waveguides have to be developed.

The easiest way to produce prototype probes usable for the millimeter wave regime is the modification of a metal coated commercially available SFM probe (Fig. 2a) using a focused ion beam. For the realization, an simple coplanar waveguide was designed, simulated and realized. Taking the geometry of commercially available aluminum and platin coated SFM probes into account a coplanar waveguide on silicon substrate has been simulated using "Linear and nonlinear microwave circuit analysis and optimization" software [9]. A line width of 17 µm for the center electrode and a spacing to the ground electrodes of 3 µm should therefore provide a 50 Ω waveguide for an optimum matching to a 50 Ω amplifier.

Based on this simulation the SFM probes were modified using an FEI 620 focused ion beam system. Gallium ions with an energy of 30 KeV were used. The system allows to use beam currents ranging from 6 pA to 7 nA. The coated SFM probe was mounted on a 5-axis stage and secondary electron imaging was used for probe alignment and control of processing steps. To create coplanar waveguides, a line structure was milled by focused ion beam enhanced etching using iodine as an etchant.



a)



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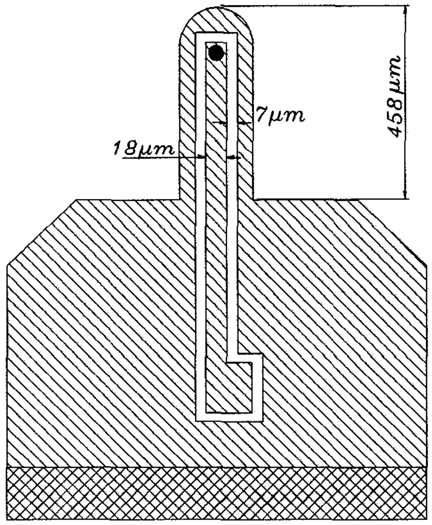

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Figure 2: a) Coated unstructured standard topography SFM probe (top view). b) Micro structured SFM-probe with coplanar waveguide (top view).c) Sketch of the realized micro structured SFM probe.

The beam current was 7 nA with a beam diameter of 400 nm. The total processing time was 45 minutes. The final structure consisted of a coplanar waveguide with a total length of about 1 mm. For process verification of the coplanar waveguide a scanning force microscope topography image was measured on the micro structured SFM probe shown in Fig. 2b. The width of the center electrode was 18 µm and the gap between the ground electrode and the center electrode was 7 µm (Fig. 2c). Fig. 3 shows a cross section of the realized coplanar waveguide in direct comparison to the simulated waveguide (principle geometry shown at the top). A small mismatch of real and simulated values (11%) forced a second simulation of the impedance using the software tool. An impedance of 44 Ω for the realized micro structured SFM probe is calculated.

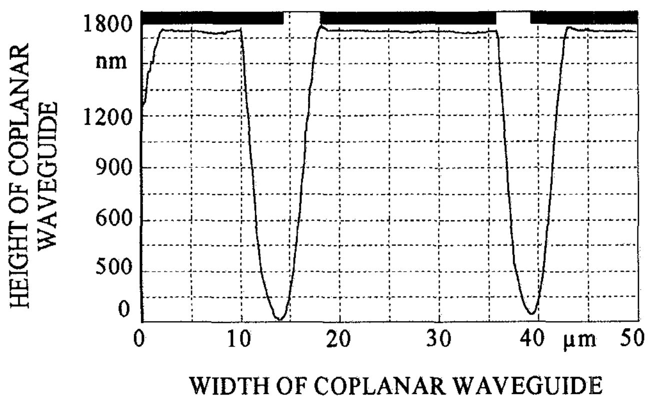
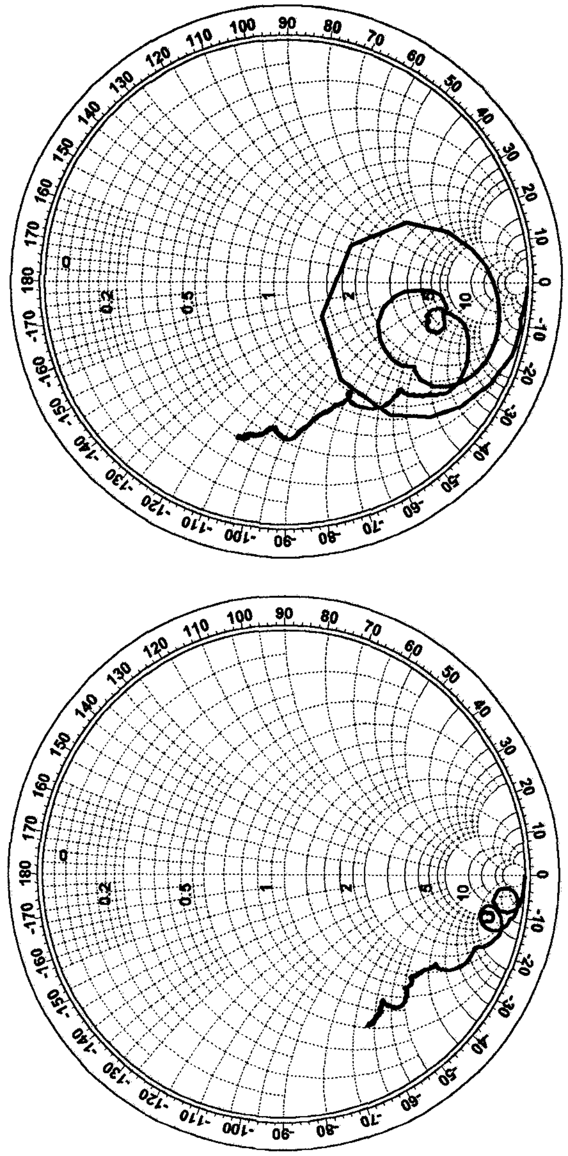


Figure 3: Comparison of simulated (black areas at the top) and measured (———) cross-section (see Fig. 2b) of the coplanar waveguide on the SFM probe.

EXPERIMENTAL CHARACTERIZATION

The unstructured and structured SFM probes have been characterized using a HP8510C network analyzer in the frequency range from 45 MHz to 45 GHz (linear frequency sweep, see Fig. 4). The SFM probes have been directly contacted with standard RF-probe tips (*Picoprobe 40A-GSG*) to avoid the degradation of the RF-behaviour due to parasitic inductances and capacitances caused by bond wires and to achieve a high measurement accuracy.



a)

b)

Figure 4: a) Input coefficient s_{11} in dependence on the frequency (45 MHz-45 GHz) for an unstructured SFM probe. b) Input coefficient s_{11} in dependence on the frequency (45 MHz-45 GHz) for a structured SFM probe with a planar waveguide.

A one-port *SOLT*-calibration with a standard calibration substrate has been performed to measure the input impedance, characterized by the scattering parameter s_{11}, of each SFM probe (Fig. 4). The coated unstructured SFM probe (Fig. 4a) shows strong variations of the input impedance in dependence on the frequency. This leads to varying signal amplitudes and increases the problems of matching the probe to a 50Ω-amplifier. In contrast to the unstructured SFM probe, the SFM probe with a planar waveguide shows a nearly linear impedance behaviour in dependence on the frequency (Fig. 4b). Figure 4b reflects an impedance behaviour which is comparable to a transmission line with high distributed resistance. Even the lower phase shift due to the lower distributed capacitance and due to a reduced effective length of the planar waveguide leads to an uncomplicated matching to an amplifier and to a nearly constant amplitude of the measured RF-signal.

CONCLUSION

A new scanning probe microscope probe for electrical millimeter wave measurements on MMICs keeping the nanometer topography imaging capability has been developed, simulated and realized. The experimental characterization shows an improvement of the electrical properties.

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REFERENCES

[1] S. E. Rosenbaum, B. K. Kormanyos, L. M. Jelloian, M. Matloubian, A. S. Brown, L. E. Larson, L. D. Nguyen, M. A. Thompson, L. P B. Katehi, G. M. Rebeiz, "155- and 213-GHz AlInAs/GaInAs/InP HEMT MMIC Oscillators", IEEE Transactions on Microwave Theory and Techniques, Vol. 43, No. 4, (1995), 927-932

[2] G. Sölkner, E. Wolfgang, C. Böhm, "New Diagnosis Techniques for sub-μm Integrated Circuits", Proceedings of the 20th European Solid-State Circuits conference (ESSCIRC), 11-17, (1994)

[3] W. Mertin, "New Aspects in Electro-Optic Sampling", to be published in: Microelectronic Engineering

[4] G. Binnig, C. F. Quate, CH. Gerber, "Atomic force microscopy", Phys. Rev. Lett. 56, 930-933, (1986)b

[5] C. Böhm, A. Leyk, J. Sprengepiel, E. Kubalek, "Advanced function- and failure analysis of monolithic integrated travelling wave amplifiers by scanning-force-microscopy", Proceedings of the 24th European Microwave Conference (EuMC), Vol. 2, 1495-1500, (1994)

[6] C. Böhm, J. Sprengepiel, A. Leyk, E. Kubalek, "Characterization of probe-tip/sample signal transmission in electrical sampling scanning force microscopy", in: Proceedings of the 25th European Microwave Conference (EuMC), Vol. 2, 1265-1269, (1995)

[7] A. Leyk, C. Böhm, D. van der Weide, E. Kubalek, "104 GHz Signals Measured by a High Frequency Scanning Force Microscope Test System", Electronics Letters, Vol.31, No.13, 1046-1047, (1995)

[8] J. Nees, "Ultrafast, Ultrafine Probe Developed", in Newsletter, Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Vol. II, No.1, 4-6, (1994)

[9] "C/NL2 for Windows: Linear and Nonlinear Microwave Circuit Analysis and Optimization", Nonlinear Consulting, P.O. Box 7284, Long Beach, CA 90807, USA