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SCANNING PROBE MICROSCOPE GIGAHERTZ MEASUREMENTS ON 200 NANOMETER WAVE GUIDES

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Abstract

Scanning probe microscopy is opening new applications in microelectronic engineering due to easy and reliable instrumentation in combination with superior resolution limits without any sample preparation under ambient conditions. Beside the standard topography imaging possible application are static and dynamic surface potential measurements, doping profiling, and scanning thermal applications. In this paper, we report dynamic voltage contrast measurements of analog and digital gigahertz signals on 200 nm wave guides within integrated microelectronic devices and components. The results are obtained by using a time resolved device internal test technique based on a scanning force microscope using the electrostatic force interaction. This technique enables voltage contrast even within passivated integrated circuits with nanometer spatial resolution and gigahertz measurement bandwidth and additionally millivolt sensitivity.

Key Words: Scanning probe microscopy, scanning force microscopy, Kelvin probe microscopy, capacitive force microscopy, Maxwell stress microscopy, voltage contrast, function and failure analysis, high frequency measurements, nanotechnology.

Introduction

Recent developments in semiconductor physics towards nanotechnology allow the production of complex microelectronic devices with structure dimensions in the sub-μm-regime and operating frequencies above 10 GHz [6]. For such devices, detailed knowledge of device internal voltage and field distributions is of crucial importance for design as well as function- and failure analysis. Because of the typical small dimensions, internal testing using mechanical probes is impossible. Only contactless test techniques can be used. But established contact-less test tools like electron-beam testing and electrooptic sampling suffer from limited spatial or temporal resolution due to physical effects [4, 5].

During the last decade, scanning force microscopy (SFM) has developed into a powerful tool to probe with superior spatial resolution in the sub-μm-regime [1]. The principle of SFM is based on the local near-field interaction of an atomically sharp tip mounted on one end of a cantilever and a sample, due to attractive or repulsive forces. The sample-tip interaction causes a detectable bending of the cantilever. Time resolved two dimensional measurements of high frequency signals can be carried out by using a SFM with a conducting tip [2, 3].

In this paper, we report gigahertz (GHz) measurements of analog and digital signals on passivated 200 nm wave guides using an optimized scanning probe tester. The results demonstrate, for the first time, the power and potential of this test technique. The achieved results cannot be obtained with other existing test systems.

Principle of Scanning Probe Testing

The principle of scanning probe testing within an integrated circuit is shown in Figure 1 for the example of a meander wave guide. The bending Δy of the conducting SFM-tip, which is in fixed height h above the sample (non-contact SFM mode), is caused by the voltage difference U between tip voltage U_s and sample voltage U_p. The effective force on the tip depends on

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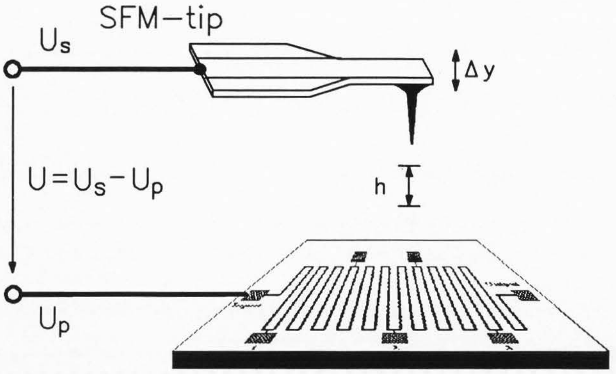


Figure 1. Principle of scanning probe testing on a meander wave guide.

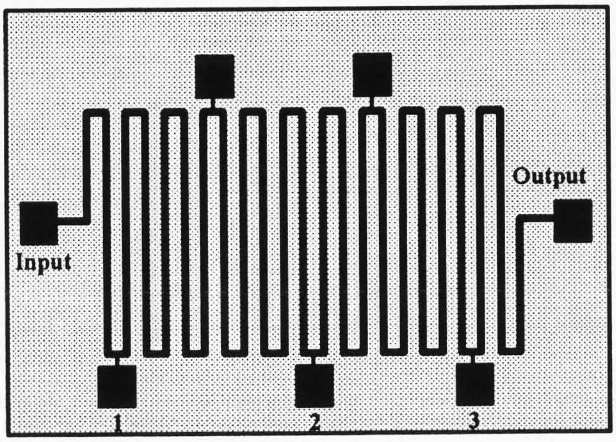


Figure 2. Principle layout of the meander wave guide sample.

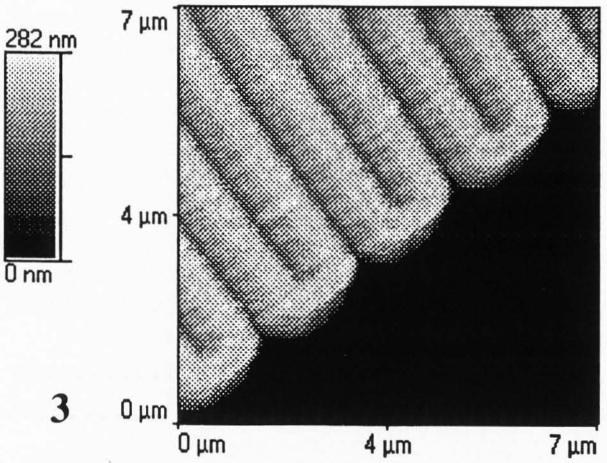
the voltage difference and the tip position. This leads to a strong dependence of the spatial resolution and the sensitivity to the effective electrical interaction area between tip and sample. Therefore, the tip-sample separation should be kept as small as possible. Modelling the geometry of Figure 1 as a plate capacitor gives a square dependence of the force on the voltage due to the electrostatic force. This means that two oscillating voltages U_s (frequency f_s) and U_p (frequency f_p) mix to frequency difference and sum terms.

In SFM, the bandwidth of the test system is normally limited by the maximum mechanical resonant frequency of the cantilever used. But, in scanning probe testing, an electrical sampling technique based on the non-linear force/voltage dependence can be applied and GHz sample signals can be measured with low resonant frequency cantilevers. Therefore, the contact-less electric tip-sample interaction serves as a down conversion mixer. If there is a small frequency difference Δf between the high frequency sample signal U_p (frequency f_p) and the high frequency tip signal U_s (frequency f_s) mixed frequency terms at the frequencies $f_s + \Delta f + f_p$ and the important $f_s + \Delta f - f_p$ occur. By this, the SFM tip oscillates at the low beat frequency Δf modulated with the amplitude and phase information of the high frequency sample signal U_p. In the experimental set-up, a system of coupled synthesizers was used to implement the electrical sampling system.

Experimental Results

For the measurements, a passivated e-beam written meander wave guide with 200 nm line width and 600 nm spacing between the lines was used. The structure was built on 150 nm poly-silicon which was doped with cobalt. The wave guide itself is thin passivated and mounted in a standard 40 pin carrier. Electrical connections to the chip are made by bond-wires. Figure 2 shows the principle layout of the device with input, output and external test points (1, 2 and 3). The experiments were carried out with a self made scanning probe tester with micro position stage which is based on a commercial scanning force microscope.

To demonstrate the high resolution limits of the scanning probe tester, we chose, in the first experiment, a small part of the wave guide near to test point 1 as test area. We scanned the topography (see Fig. 3, topography SFM image of the 200 nm wave guide) and positioned the SFM tip in a fixed height of 50 nm above the centre of the wave guide. We fed a 1 GHz analog signal with 5 dBm amplitude onto the chip and measured, in the time domain, the amplitude of the sample signal (see, Fig. 4). For this purpose, a 1 GHz + 11 kHz sampling signal was applied to the tip. The result is ten times averaged and shows a high quality measurement of the signal shape (measured at the beat frequency of 11 kHz) of the device internal signal with 1 nm positioning accuracy. The shown amplitude corresponds directly to the amplitude of the unknown sample signal and the time-axis can be rescaled to the known frequency (1 Ghz) of the sample signal. Going one step further, we image not only the amplitude of the device internal signal in a non-invasive way at one point but scan the tip above the device and collect the amplitude information of every measurement point via computer and generate a voltage contrast image (see, Fig. 5). The tip-sample working distance during the scan is fixed to a constant height by external feedback to the SFM electronics. The scan area was 7 μm x 7 μm. In the voltage contrast image, black areas correspond to low voltage levels, and white areas correspond to high voltage levels. The scale is in arbitrary units (scaled from 12.18 nA to 14.45 nA detector current).



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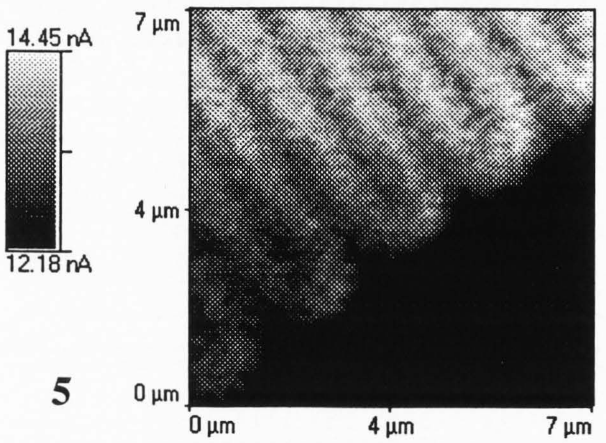

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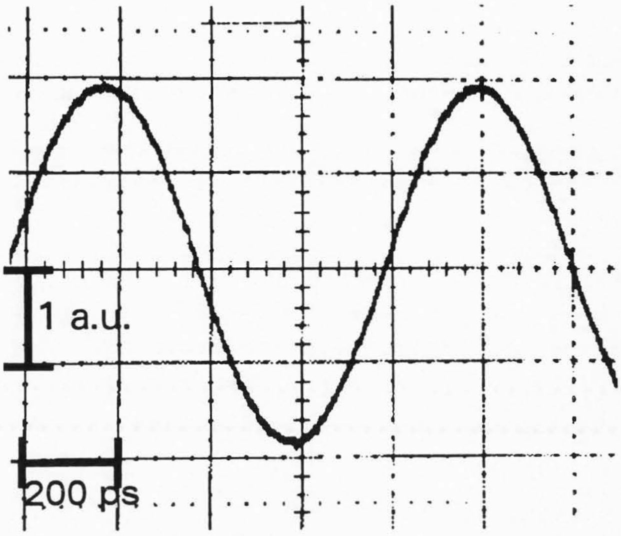
Figures 3 and 5. Topography image (**Fig. 3**) and the corresponding 1 GHz voltage contrast image (**Fig. 5**) of the test area near test point 1.

Figure 4. 1 GHz device internal analog signal near to test point 1.

Figures 6 and 7. 3.2 GHz / 3.3 V device internal digital signal near to test point 1 (**Fig. 6**) and near to test point 3 (**Fig. 7**).

The voltage contrast image shows the voltage distribution on the wave guide at 1 GHz and can be correlated to the topography from Figure 3. As one can see, there is a small tilt in the measured signal amplitude from the upper right to the lower left side in the image. This artefact results from a drift in the external feedback signal causing a larger tip-sample height. This artefact can be removed by software manipulation. The image consists of 20,000 data points collected in 2 minutes.



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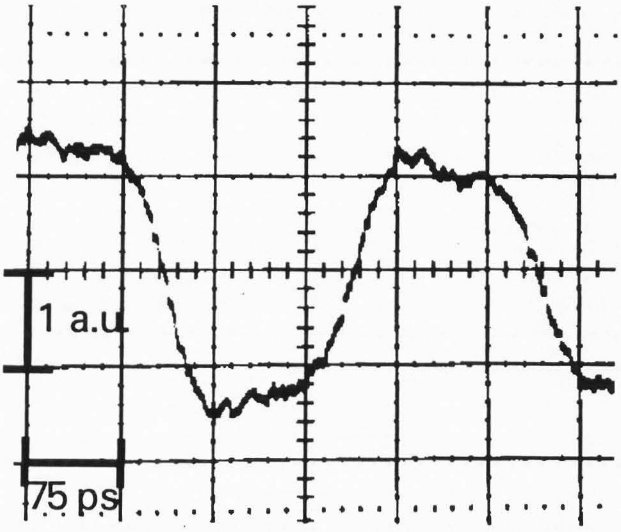

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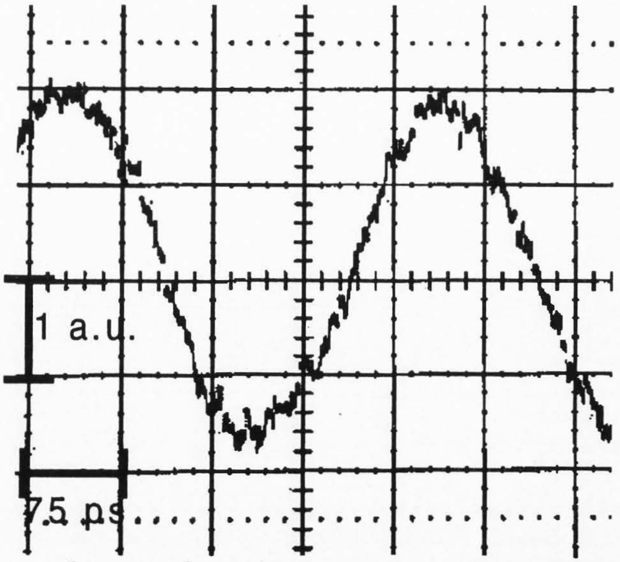

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In a second experiment, we probed digital 3.2 GHz signals of 3.3 V amplitude (produced by a HP 8133A synthesizer) within the same sample. The experimental set-up stays unchanged, only the signal source was exchanged. Again, we imaged first the topography within the device to estimate two test points near to the external test points 1 and 3. Then, we positioned the tip in a fixed height of 50 nm above the centre of the wave guide and probed the device internal digital signals. Figures 6 and 7 show the signals near test points 1 and 3, respectively. For the measurement of signal with digital shape, a 100 ps sampling pulse with a repetition frequency of 100 MHz (plus a beat frequency of 150 Hz) was applied to the tip. The shown wave form is rescaled to the time-axis of the sample signal (3.2 GHz). Significant differences occur in the two measured signals. In Figure 6, not even a sharp signal rise, but clearly a digital signal shape can be seen. This internal signal was compared to external voltage measurements on test point 1 and both show exactly the same shape. In Figure 7, the measured signal is no longer digital but now sinusoidal. This is caused by dispersion of the input signal on the 200 nm wave guide. After travelling over 12 cm wave guide to test point 3, the signal is deformed and only the ground harmonic is with significant amplitude on the wave guide. Higher harmonics are damped. Based on these experimental results, we will focus further work on signal tracing of Ghz signals on passivated nanometer wave guides in combination with improved interpretation of the experimental results by using an approach for quantitative high frequency wave form measurements.

Conclusion

A new contact-less measurement technique based on a scanning force microscope for non-invasive device internal voltage measurements with nanometer spatial resolution and gigahertz measurement bandwidth has been introduced. Experimental results on passivated 200 nm wave guides demonstrate the power and potential for applications in nanotechnology devices.

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Editor's Note: All of the reviewer's concerns were appropriately addressed by text changes, hence there is no **Discussion with Reviewers**.