Near-field Antenna as a Scanning Microwave Probe for Characterization of Materials and Devices

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Abstract—**The Scanning Microwave Probe (SMP) is emerging as an important broadband metrology tool for characterizing materials and devices in the micron and sub-micron length scales in the frequency range of 10 MHz to 110 GHz. In this document we establish three important characteristics of SMP: 1) the sensitivity of this tool to the materials properties by showing data in the conductivity range of 0 to 2000 S/cm in a stratified medium; 2) the breaking of the λ/2 barrier for spatial-resolution where we report measurement of 1μm spatially resolved features at the frequency of 4.6 GHz on SiGe sample; and 3) detection of sub-surface structures under 2 metal layers in an 8-layer CMOS IC with a measured 0.3% change in Q-factor at 1.8 GHz.**

I. Introduction

With new materials enabled by nano-fabrication, there is a need to develop nano-scale metrology tools. Many important problems in nanoscopic and mesoscopic physics require measurement of materials property like complex conductivity, complex permittivity and complex permeability with almost atomic spatial-resolution. For device engineering, the charge and spin dynamics have to be studied not only with high spatial resolution but also with high sensitivity which can detect ideally a single charge or spin. In addition, the measurements must be broadband and non-destructive, if they are supposed to address the behaviour at operating frequencies.

For frequencies from several MHz to 110 GHz, the Scanning Microwave Probe (SMP) technique is the primary approach to study such problems. The SMP operation is based on near-field reactive loading of an electrically small antenna probe by the sample of interest (or DUT) where the probe-to-sample distance is much smaller than a free-space wavelength. In the near field the spatial resolution is dictated by the distance from the antenna to the sample and the size of the antenna probe tip, which circumvents the Abbe limit of λ/2 for spatial-resolution. Hence the challenge for SMP is to keep the probe-to-sample distance small and design the antenna with appropriate characteristic dimensions. Two methods that accomplish this are discussed in Section II below.

In this document we will consider some of the experimental milestones achieved in relation to SMP. However, it is important to note that one of the major challenges in the field is the extraction of local physical and electrical properties of the sample. Elaborate electromagnetic and optical models are used to this end.

There are many ways to model the SMP problem and it is discussed in the literature in detail [1]. For brevity we summarize two simple electromagnetic near-field antenna modelling technique. The near-field probe can be modelled with a small Hertzian electrical dipole above the sample (labelled as Thin-film or Device in Fig. 1). The height and dipole size are both much smaller than the excitation wavelength λ. The fields are determined at the surface of the thin-film/device to calculate the dissipated power in the sample [2,3] and thus quantifying the loading of the probe. An alternative modelling method for the extraction of sample properties is the lumped element model [4-7]. In the next section, the experimental aspects of the SMP are briefly overviewed.

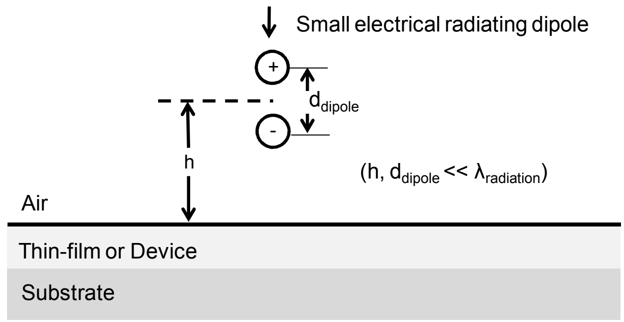
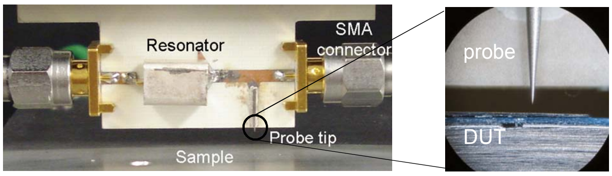


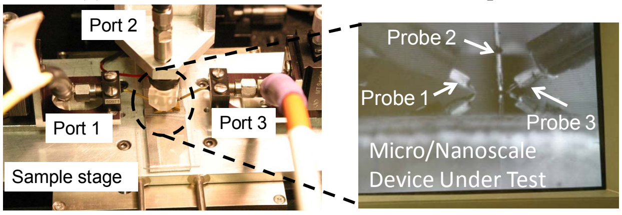
Fig. 1 The Hertzian dipole antenna above the sample. The important condition for SMP is that h, $d_{dipole} << \lambda_{radiation}$.

II. Experiment

A few commercially available SMP systems currently available are targeting niche markets to fulfil metrology needs in the semiconductor industry [8]. Two in-house systems developed for research are shown in Fig. 2. The SMP instrument is comprised of a near-field antenna (or probe) coupled to a resonant circuit. Fig. 2(a) shows the resonant probe circuit, and near-field antenna developed for the in-house SMP system at UC-Boulder. The resonator is a small, surface-mount λ/2-open coaxial transmission line and the near-field tip is a sharp tungsten probe. The multiple resonances of the transmission line resonator (where $L_{res} = n\lambda_0/2$) allow a device to be characterized at many frequency points. The SMP system scans the DUT beneath the probe (as shown in inset of Fig. 2(a)) with computer controlled mechanical and piezoelectric *xyz* motion stages. The loaded resonator impedance is measured at each point in the scan area, and DUT characteristics are spatially determined. The impedance can be measured through a standard Vector Network Analyzer (VNA), or a custom IQ demodulator and lock-in amplifier. The reference frequency for the lock-in amplifier modulates either the RF local oscillatoror the z-axis scanning piezoelectric motion stage for enhanced SNR.



(a) UC-Boulder in-house SMP circuit and probe



(b) NIST-Boulder in-house SMP system

Fig. 2 In-house SMP experimental setup photos showing the a) CU Boulder SMP resonant probe circuit and near-field antenna probe tip, and the b) NIST Boulder 3-port SMP system with STM feedback on Port 2 for high spatial-resolution imaging.

Fig. 2(b) shows a Scanning Tunneling Microscope (STM) based SMP system. It is a custom 3-port system built at NIST which enables measurement of all 9 S-matrix elements. Port 1 and Port 3 are conventional GSG probes, while Port 2 is a transmission line resonator of a given length L where any excitation wavelength (satisfying the condition, $L_{res} = n\lambda_0/2$ where n is the mode number) can be used in the case of the resonator. The center conductor of the transmission line is modified [4] to hold a very sharp STM tip which serves as the near-field antenna (Probe 2 in the inset of Fig. 2(b)). A bias-Tee isolates the DC and AC paths to simultaneous lock the STM feedback (DC) and measure the microwave response of the sample [4]. This keeps Probe 2 at a nominal height of 1 nm above the sample. A probe radius of curvature on the order of 10–100 nm yields a spatial-resolution of the same order (10–100 nm). Alternatively, one can also measure the shift in the resonant frequency of the resonator (Δf) and the Quality Factor (Q) by placing a well designed high-Q resonator. Instead of a high-Q resonator, an optical probe can be placed here at the location of Port 2 as well due to the versatility of such multi-port systems.

III. Results

We discuss, as mentioned above three demonstrated functions of SMP systems: 1) materials contrast; 2) high-spatial resolution; and 3) sub-surface device detection.

A. *Materials Contrast*

Figure 3 shows measurements of Indium Zinc Oxide thin films with conductivities of 0.0015 S/cm, 160 S/cm and 2000 S/cm. The y-axis is the product of the Δf and Q of the resonator and the x-axis is the height above the sample starting from a "soft" touch on the sample (labelled as "touch-point" in Fig. 3). The Q x Δf on the y-axis is an important quantity as it is the measure of the Z_{in} [9] of the resonator. The sample changes the Z_{in} yielding the contrast in the Q x Δf signal.

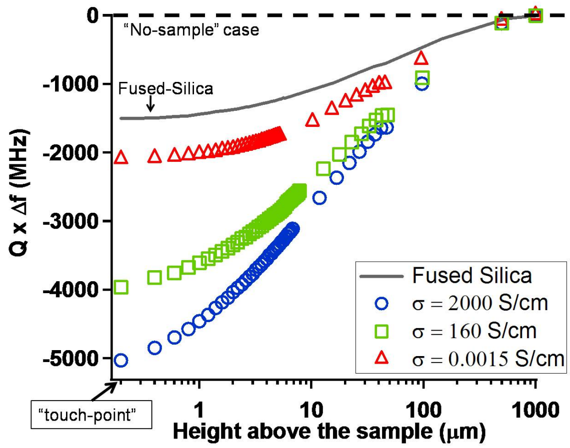


Fig. 3 The materials contrast based on conductivity (in S/cm) for three different films with a commercial SMP. Measurement frequency is 2.66 GHz. For comparison the data on bulk dielectric (Fused Silica) is also shown.

The data clearly shows that the SMP measurement allows one to distinguish between the three conductivities with highest signal contrast for the 2000 S/cm data and the lowest for the 0.0015 S/cm film. For reference, we measure Fused Silica which is a bulk material (solid line in Fig. 3). In the case of no sample, the Δf is zero showing no change in the signal (labelled as 'No-sample" case in Fig. 3).

B. *High Spatial-resolution*

Fig. 4 shows a measurement of a SiGe sample using one of the commercially available SMP systems. It is very similar to the STM based system except here the DC feedback is provided by the atomic force microscope (AFM) in the contact mode. The resonator is directly attached to the VNA and the $|S_{11}|$ and phase are measured in reflection. In this system there is an additional derivative signal (dC/dV) available to make spatially-resolved measurements of the dopant concentration. This signal is acquired with a lock-in technique where 75 kHz of modulation frequency is used to lock near the minimum of the resonance in the S_{11} signal. The in phase output of the lock-in amplifier is proportional to the dopant concentration.

The sample is SiGe in the doped form of stripes of different widths [10]. The closest spaced stripes on this sample are 1 μm apart (marked by white arrow in Fig 4a-c). The images in Fig. 4 are 100 μm square in size each and have been simultaneously acquired. As is clear from the data, there is strong correlation between the microwave images and the topography. This demonstrates the power of SMP to spatially resolve at least as well as the AFM itself, because in the near-field the radius of curvature of the tip determines the spatial-resolution and not the wavelength of measurement. So with this SiGe sample the spatial-resolution is as good as 1 µm with a measurement wavelength of 65 mm. With STM feedback spatial-resolution on the order of 2.5 nm is reported for capacitance [5] and 100 nm for resistance [5].

Comparing Figs. 4a-d, one notices that the dC/dV signal does not have the irregularity in the lower part of the sample which the other three images have. Since they are mainly topographic defects, the dC/dV is not sensitive to them. We expect this since the derivative signal should only be sensitive to the dopant concentration in SiGe.

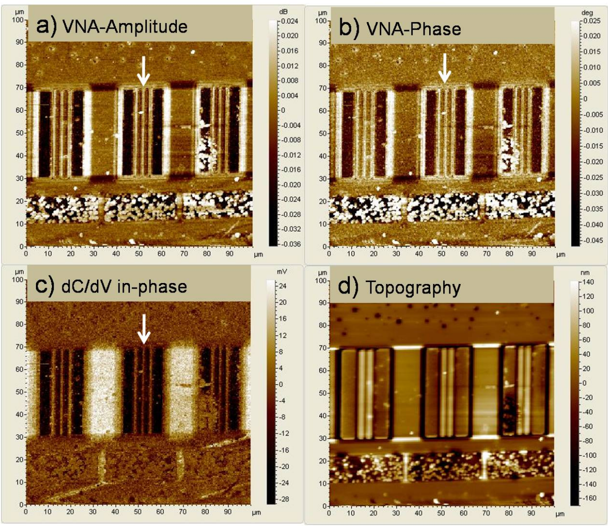


Fig. 4 High Spatial-resolution at 4.6 GHz. a) VNA-amplitude (S_{11} signal), b) VNA-phase, c) dC/dV signal in phase and d) AFM-topography. The doped stripes are 1 µm in width (pointed by the white arrows in a-c).

C. Devices

Figure 5 shows measurements of a CMOS IC test structure conducted at 1.8 GHz with the CU-Boulder SMP system (as shown in Fig. 2a). A 15 µm diameter near-field probe tip is scanned 20 µm off the device surface in 7.5 µm *x* and *y* steps. The IC has 8 metalized layers with two 10 µm bus lines two layers below the surface. The top two layers (covering the bus lines) are comprised of metal fill (5 µm x 5 µm metallic square grid shown in inset of Fig. 5(a)) that obstructs the majority of the signal for the measurements of the bus lines. The measured Q-factor of the probe resonator is shown to change by as much as 0.3 % (with resonator of $Q_0 = 650$) due to the sub-surface bus lines demonstrating detection of sub-surface features.

IV. Conclusions

In this document, we have shown the sensitivity of SMP to the material contrast and its ability to distinguish between thin-films of different conductivities in the range of 0.0015 S/m to 2000 S/m. We have also shown data to establish the 1µm spatial-resolution in the SMP signal. We also demonstrate sub-surface detection of 10 µm IC features.

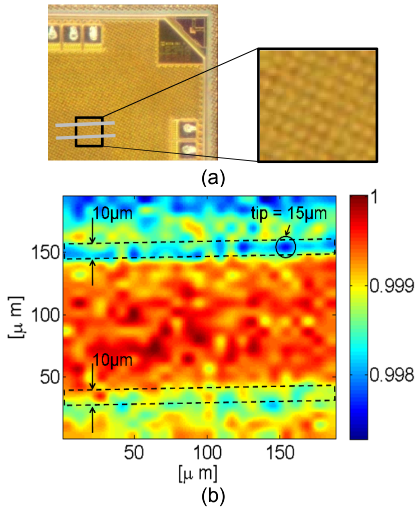


Fig. 5 (a) Two layers of metal fill (5 µm x 5 µm metallic square grid shown in inset) form a "Faraday cage" above two 10 µm bus lines of an 8-layer CMOS IC. (b) Q scans at 1.8 GHz with a 15 µm diameter probe tip allow detection of bus lines through the two metal grid layers.

Acknowledgment

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