Characterization of semiconductor structures using scanning microwave microscopy technique

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***Abstract*—In this work, we have developed a near field scanning microwave microscopy method and applied it to study semiconductor samples. To do so, we have used a commercial Atomic Force Microscope (NT-NMDT Integra) to which we have coupled a half wavelength micro-strip line resonator and an Agilent N5242A PNA-X Network Analyzer. The AFM tip is connected at the edge of the microstrip which is connected to the PNA. The reflection coefficient S_{11} is measured as the tip is scanned, at some distance and without contacting it, on the device under test. The variations of the S_{11} parameter are related to the topographical and dielectric properties of the material under the tip.**

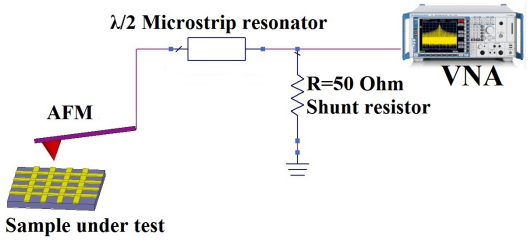


Fig. 1. Experimental setup of the combined SMM-AFM technique.

I. Introduction

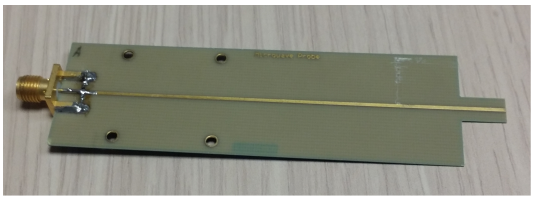
The characterization of materials can be achieved by examining the interaction of electromagnetic fields with matter[1,2]. Near-Field Scanning Microwave Microscopy (NFSMM)[3] is one of such tools which has been proposed for non-destructive characterisation of localised material electrical properties at microwave frequencies[4,5,6]. In the near-field regime, quantitative measurement of these properties can be carried out on length scales much smaller than the freely propagating wavelength of the radiation[7,8,9]. When a sharp probe tip protruding from a resonator cavity of high quality factor is made to approach the sample surface with close proximity, near-field microwaves can be utilised to obtain measurements of the reflection coefficient S_{11}, quality factor and resonant frequency shifts of the resonant cavity coupled to the tip[9]. Local material electrical properties such as conductivity, sheet resistance and dielectric constant, etc. can then be extracted from the measured data [4,10]. Of particular interest is the study of the electrical conductivity of thin film samples, including semiconductor nanostructures [11,12,13,14,15]

In the approach followed in the present work, a performance network analyzer (PNA) continuously feeds the conductive tip of an atomic force microscope (AFM), to which we have coupled a half wavelength micro-strip line resonator. The tip is then approached to the surface of the sample under study using the AFM control mechanism[16], operated in the usual way. Depending on the impedance of the tip-sample interface, part of the microwave signal is reflected and measured by the PNA as the reflection coefficient, S_{11}. The S_{11} parameter depends on the dielectric properties of this region, and therefore the high spatial resolution of the AFM allows us to non-destructively characterize semiconductor structures with high sensitivity and with nanometer resolution, evaluating for example the quality of the interfaces, thickness variations, doping and carrier concentrations, etc. [17,18].

II. Experimental Setup

Several commercial NFSMM solutions are already available[19]. However, in this work we have developed a home-made adaptation to easily convert a commercial AFM in a NFSMM device. To do so, we have coupled a $\lambda/2$ micro-strip resonator to a commercial AFM (NT-MDT Integra) by adapting a specific tip holder. The conductive tip (n-doped silicon tip coated with gold) is connected at the edge of the micro-strip in contact with the conductive line of the micro-strip (Figure 1 and Figure 2). To check the validity of the set-up, the device under test in this work, consists in a silicon sample, covered with 300nm of SiO_2. Different patterns of gold and aluminum with different sizes and shapes are deposited on top of the oxide by thermal evaporation. This structure is used to calibrate the system (Figure 3). The thickness of the gold metallization is 60-70nm.

Figure 1 shows a scheme of the setup used in this work, and Figure 2 shows some photos of the microstrip and the final setup. Once the microstrip is coupled to the AFM with a home-made specific holder, the conductive probe tip is placed in contact with the edge of the microstrip, and the latter is connected to the PNA (Agilent N5242A PNA-X Network Analyzer) and a frequency sweep is performed typically from 10Mhz to 26.5 GHz. Figure 4 shows the magnitude of the $|S_{11}|$ parameter as a function of the frequency. The selected fixed frequency for the experimental procedure was $f_0 = 3.36$



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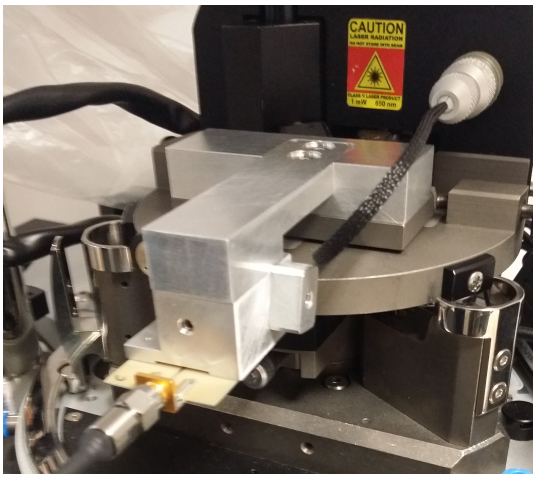


(b)

Fig. 2. a) 1/2 wavelength microstrip resonator, b) Homemade SMM-AFM holder

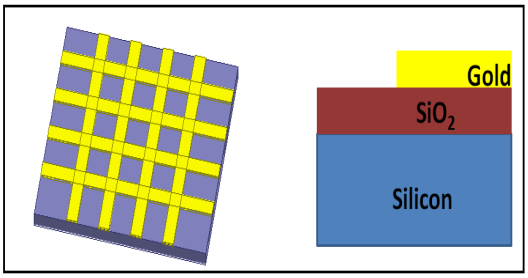
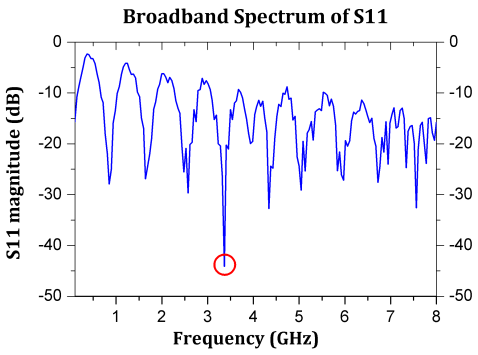


Fig. 3. Squeme of sample under test

GHz (Figure 4-b). Figure 4-c shows $|S_{11}|$ when the tip is in air configuration (far away from the sample), and when is very close to the DUT at different positions: closer to the SiO_2 or closer to the gold metallization. When the tip is approaching the sample, we see that there is a significant decrease in the S_{11} amplitude, a broader bandwidth as well as a shift of the S_{11} signal peak towards a lower frequency value as compared to Fig. 4(b). These changes can be attributed to the change in the coupling between the tip and sample.

III. Results and Discussion

Figure 5 shows AFM images of the sample under test. Figure 5-a shows the 3D topography image of the area of the



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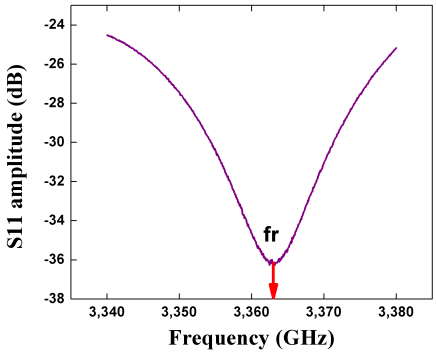

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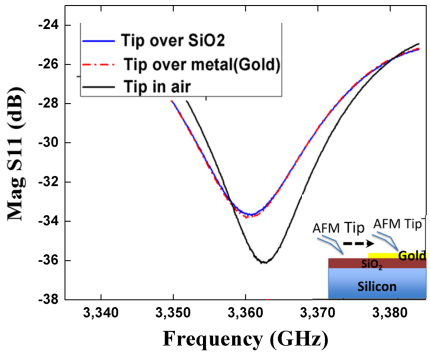
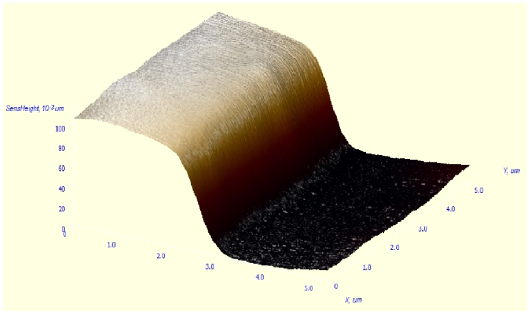


(c)

Fig. 4. a) $|S_{11}|$ as a function of the frequency b) Selected working frequency, c) Changes of S_{11} and f_r when tip above the sample.



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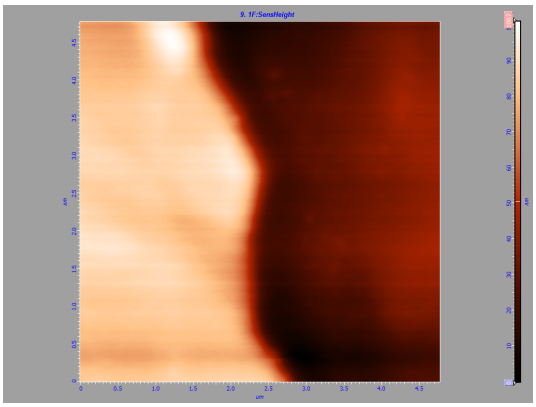

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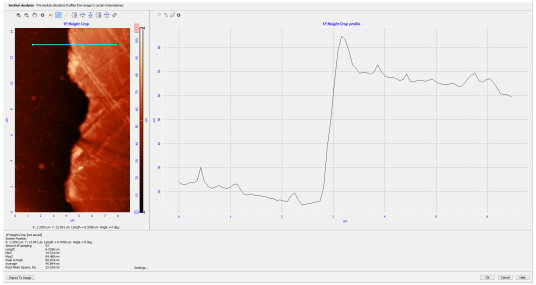


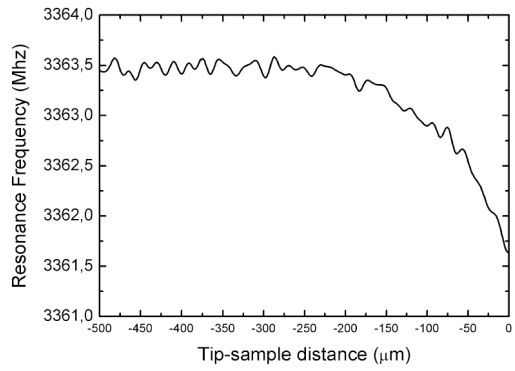
(c)

Fig. 5. a) 3D topography image of the scanned sample, b) 2D topography image of the sample, c) Profile of the sample under test –SiO_2 and metal high level.

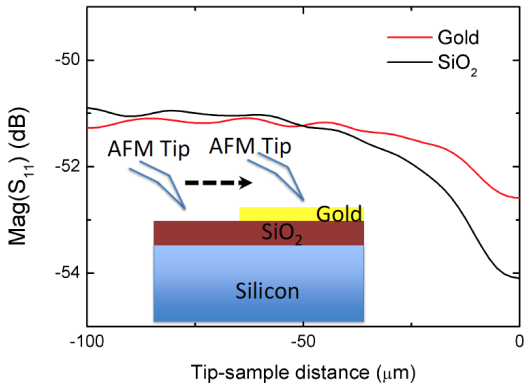
sample scanned, while Figure 5-b show the 2D topography and Figure 5-c the suface profile between the SiO_2 and the gold metallization.

Once the DUT is placed in the AFM sample holder the tip is approached to the sample and the resonance frequency, the reflection coefficient at the resonance frequency and the quality factor of the microstrip at the resonance frequency are recorded as a function of the sample-tip distance over different areas of the sample (over SiO_2 and over metal)

As the tip is approaching the sample, the resonance frequency of the microstrip remains constant until around $150\mu m$ above the sample. A closer distance from the tip to the sample surface produces a decrease of the resonance frequency, until the contact is produced. The magnitude of the S_{11} parameter



(a)



(b)

Fig. 6. a) Evolution of the resonance frequency, f_r, as the tip is approaching the sample. b) Changes in magnitude of S_{11} as the AFM tip is approaching the surface of the DUT: (red line) the approaching is produced over a point on the gold metallization; (black line) the approaching is produced on the SiO_2 substrate.

also decreases as the tip is approaching the surface of the sample, and the value that this parameter gets near and right at the surface strongly depends on the local dielectric characteristics of the semiconductor sample right under the tip. When the probe tip comes into contact with the metallic thin film samples, the S_{11} peak from VNA will become unstable and disappear such that the magnitude of S_{11} approaches 0. Hence, it is important that the tip is adjusted so that it approaches the thin film sample surface with a tip-sample distance maintained at several hundred nanometers or microns. Depending on the point where the approach is produced, the value of the reflection coefficient, S_{11}, (shown in Figure 6), the resonance frequency and the quality factor of the microstrip are modified. The scanning of the tip on the surface will produce a map of the variations of $|S_{11}|$ on the surface of the DUT, with the spatial resolution that allows the spatial resolution of the AFM. The modifications of these parameters are related to the local properties of the DUT. Although the maximum difference in the $|S_{11}|$ value is produced right at the surface, there is also a noticeable difference hundreds of nanometers above the surface. Therefore, the spatial variation of the properties of

the DUT can be detected with this technique without touching the surface, and therefore without producing any defect in the sample. In addition, this technique can also be used to detect changes in the properties of the DUT under the surface, just as doping, carrier concentration, defects, etc..

IV. Conclusion

In this work, we have developed a near field scanning microwave microscopy method. We have used a commercial Atomic Force Microscope to which we have coupled a half wavelength micro-strip line resonator and an Vector Network Analyzer. By taking advantage of the near-field regime, high spatial resolution measurements can be made. The measurement data was acquired in the form of shifts in the resonant frequency and changes in the magnitude of S_{11} when the tip of the AFM is scanned on the device under test. The variations of the S_{11} parameter are related to the topographical and dielectric properties of the material under the tip.

Acknowledgment

The authors would like to thank the financial support of Spanish Government (TEC2014-59730-R), OTRI-UGR, and ERASMUS MUNDUS AL-IDRISI project.

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