Advanced Characterization of Semiconductor Materials using Nano-Observer II AFM

Introduction

The electrical characterization of semiconductor materials is essential for understanding their properties and performance. Utilizing Atomic Force Microscopy (AFM), this advanced technique enables precise measurements at the nanoscale, offering detailed insights into electrical properties and aiding in the development of high-performance semiconductor devices.

AFM Techniques for Semiconductor Research

1. HD-KFM (High-Definition Kelvin Force Microscopy)

HD-KFM is a resonant AFM mode that provides high spatial resolution and sensitivity by measuring surface potential without lift-mode separation. This technique is crucial for mapping electrical properties at the nanoscale, helping identify different regions in semiconductor materials that impact device performance like a transistor gate, semiconductor oxides, etc.

This technique allows measurement of the surface potential between the tip of the AFM and the surface which can be related to material properties like the work function or the bandgap:

$$V_{POTENTIAL} = \frac{\Delta\varphi}{e} = \frac{\varphi_{tip} - \varphi_{sample}}{e}$$

In Fig1. It is shown the schematics of the HD-KFM approach developed by Concept Scientific Instruments. In this mode, two lock-in are used with two independent operating feedbacks. One of the is used to track the topography (by exciting mechanically the first eigenmode frequency of the cantilever) and the other to track the surface potencial (by exciting electrically the cantilever at its second eigenmode frequency).

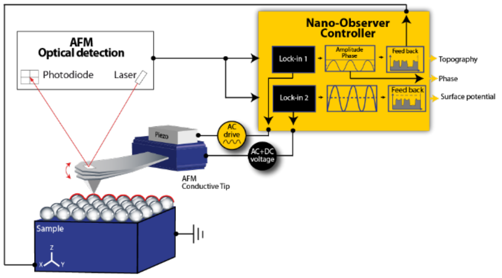
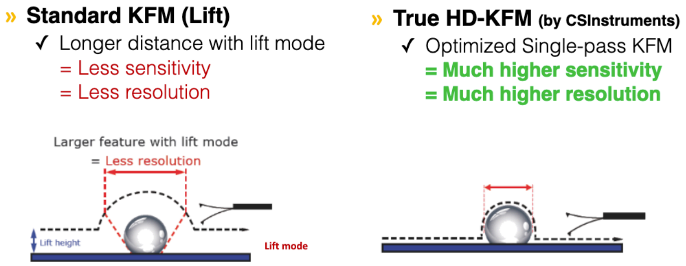


Fig.1 Schematics of HD-KFM mode.

Figure 2 shows one of the key points that explains why HD-KFM provides higher sensitivity and resolution as compare to standard approach for KFM typically based on double-pass or lift technique approach. Unlike the standard KFM mode, HD-KFM eliminates the lift between the tip and the sample during the measurement. As surface potential measurement is based on the detection of the electrical field between the tip and the sample, HD-KFM is capable to probe it closer to the surface where the intensity of the field is much higher.



In addition, in HD-KFM the electric signal is amplified through the second eigenmode resonance. Other advantages to mention about HD-KFM is the possibility to be combined with MFM for simultaneous mapping or both magnetic information and surface potential. For more detailed information about HD-KFM please download “HD-KFM appnote” or check videos on www.csinstruments/videos.

2. ResiScope

ResiScope is a contact AFM mode that measures resistance and current mapping over a 10 orders of magnitude keeping the sensitivity in every range. This mode is essential for identifying electrical properties and defects in semiconductors, crucial for device optimization.

Key Features of ResiScope Mode:

Real-time Measurement Over 10 Decades:

- Allows real-time electrical characterization from 50 fA (1Tohm) unto 1 mA (1 kohm) without user intervention.

Protective Current Level:

- Set a protective current level to prevent sample damage.

Figure 3 shows the schematics of the Resiscope module. The ResiScope electronics has an advanced DSP capable of selecting in real time the appropriate current to voltage amplifier depending on the local resistivity of the area below the tip during the surface scan. In addition, Resiscope provides the possibility of including a protective resistance that limits the maximum current flowing through the sample. This allows to limit the maximum current flowing trough tip and sample. In this manner undesired side effects like local oxidation or cantilever self-heating are minimized.

Figure 4 illustrates the advantages of using ResiScope approach as compared to other standard approaches.

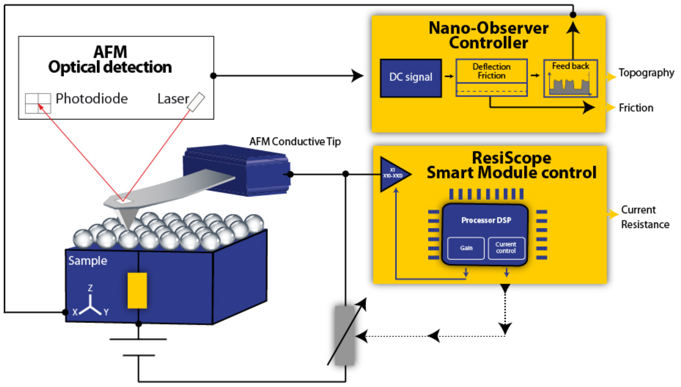


Fig.3 Schematics of ResiScope mode.

Typically each current range of the sample requires an specific current amplifier depending on the conductivity of each region of the sample: isolant domains have typically pA range which requires a low noise amplifier that can be easily saturated. In that situation, the user has to change manually the setup to adjust the amplifier to avoid saturation when measuring other domains with higher conductivity (nA range). This can be complicated to handle by the user as typically it can be easy to find conductive (µA or mA range) and isolant regions in the same area. Thus with a standard configuration both types cannot be measured at the same time.

For more detailed information about HD-KFM please download “ResiScope appnote” or check videos on www.csinstruments/videos.

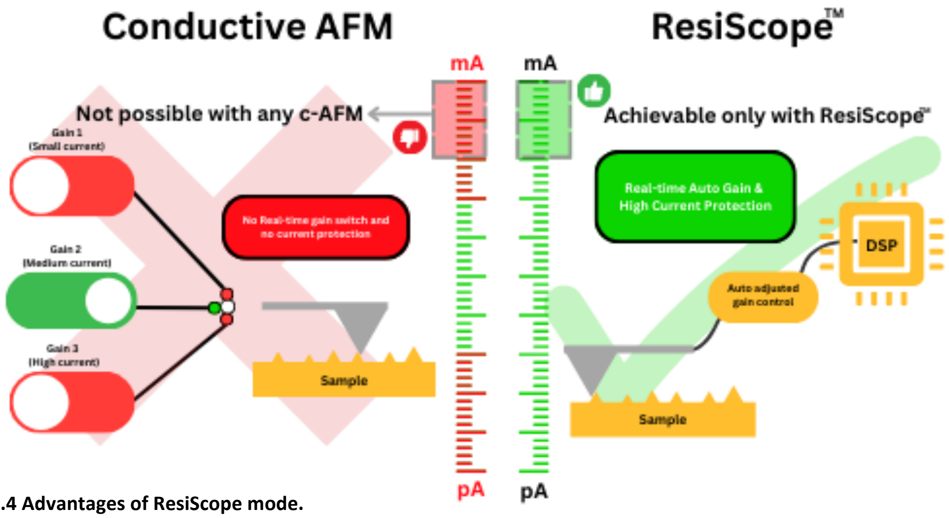


Fig.4 Advantages of ResiScope mode.

2. Soft ResiScope

Soft ResiScope provides same benefits of ResiScope (see previous section) in terms of conductive measurement while avoiding the friction generated during the scan in contact mode. Thus the Soft ResiScope benefits from the advantages of contact mode (straightforward relationship between force and deflection with Hooke's law) and resonant mode (avoiding friction and adhesion).

Soft ResiScope mode is based on the Soft-IC mode which is illustrated in Figure 4. It involves several steps depicted in the figure from (1) to (4):

(1) The AFM probe is pushed linearly against the sample surface from the non-contact (fully separated) position. This is illustrated in the top red graph "Piezo Z Displacement" as a linear ramp and in the bottom green graph "Setpoint" it is appreciated as a linear increase of the deflection from the steady horizontal deflection (tip is out of contact with the sample). In this region it is also possible to measure the contact stiffness and calculate mechanical properties (See "Mechanical Properties Appnote and more info on www.csinstruments.eu).

(2) The tip is holded for a small period of time at constant deflection(setpoint) value. In this region the bias is applied between tip and sample so that current can be measured in quantitative conditions, i.e. the force is constant during the current measurement.

(3) Once the current measurement is performed, the tip is completely separated from the sample (piezo displacement shows a linear ramp). Deflection (bottom green curve) shows typically linear decrease of the deflection until adhesion force cannot hold the tip contact anymore. In this region adhesion or "Pull-off" force can be calculated.

(4) Once the tip is completely separated from the sample, the tip is moved to the next pixel in the image.

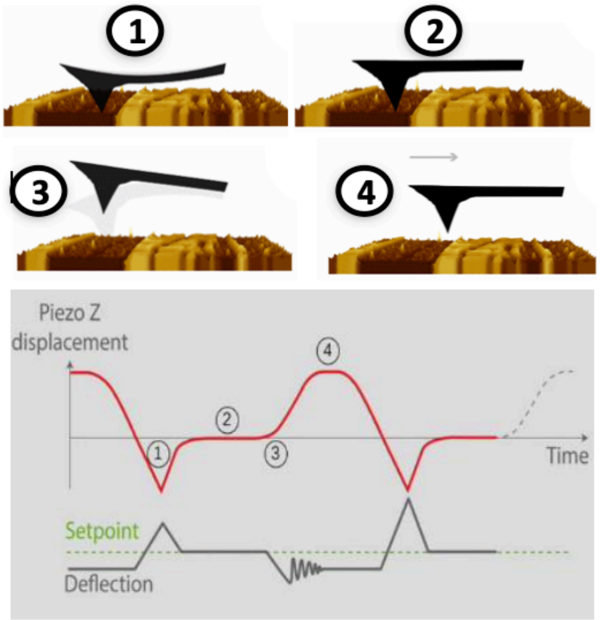


Fig.5 Illustration of Soft ResiScope mode steps.

Figure 5 shows a direct comparison between a ResiScope and a Soft ResiScope measurement to prove that both modes provide same quantitative current/resistance results. Measurement was made on an SRAM memory which shows different conductivity for drain, source and channel areas. The top part of the image was scanned in Soft ResiScope mode, while the bottom part of the image was scanned in standard ResiScope mode.

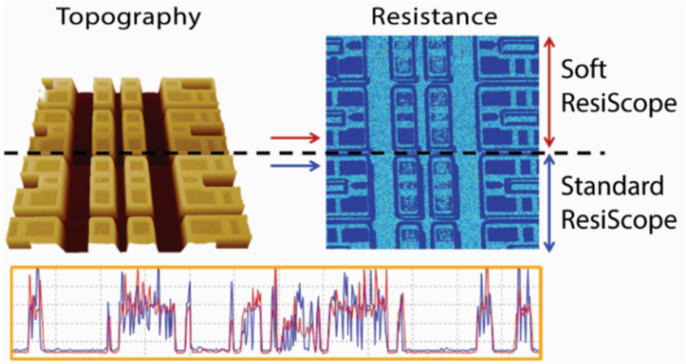


Fig.6 Comparison of ResiScope and Soft ResiScope on SRAM.

Analyzing a Vanadium Dioxide with soft ResiScope mode

VO2 is a semiconductor oxide which has attracted a huge interest in semiconductor and energy research since 1959 when Morin reported for the first time the evidence of the semiconductor-metallic phase transition (SMT). The attention given to this material is due to its extraordinary behavior of changing the electrical as well as the optical properties during the SMT from the semiconductor state (rutile crystallographic structure), to the metallic state (monoclinic structure). This phase transition takes place at a critical temperature of about Tc ≅ 68°C.

By employing Soft ResiScope, we can effectively highlight its cristal grains structure both in topography (Fig. 6-left) and current (Fig. 7-right) at room temperature (295 K). As it is well below the phase transition, crystal grains show small conductivity below 1 nA with 1 V bias applied. As depicted in the cross-section there are variations among grains from 300 pA upto 650 pA. Standard conductive ANSCM-PT tips (AppNano Inc, USA) was used with an applied force of 1.8 nN and a lift height separation of 20 nm.

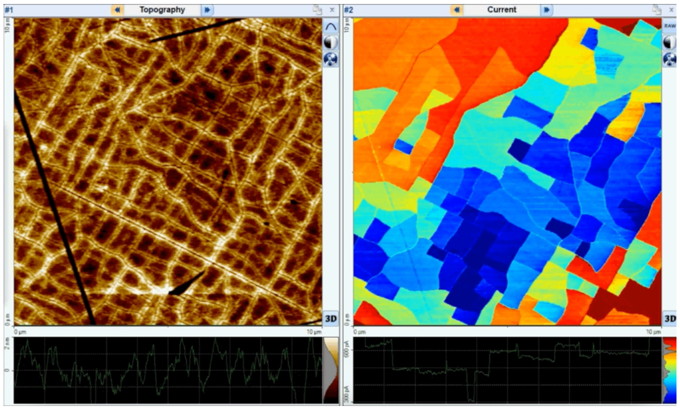


Fig.7 Topography (left) and current (right) of VO2 .

(Soft) ResiScope is compatible with add-on accesories like sample temperature controller. This accesory allows to carry out AFM measurements under sample temperature control. The smart design of the Nano-Observer AFM together with the highly dissipative heating stage allows to minimize drift derived from sample temperature changes (see Fig. 7 inset). This is of great importance to maintain the position stability as the temperature is changed.

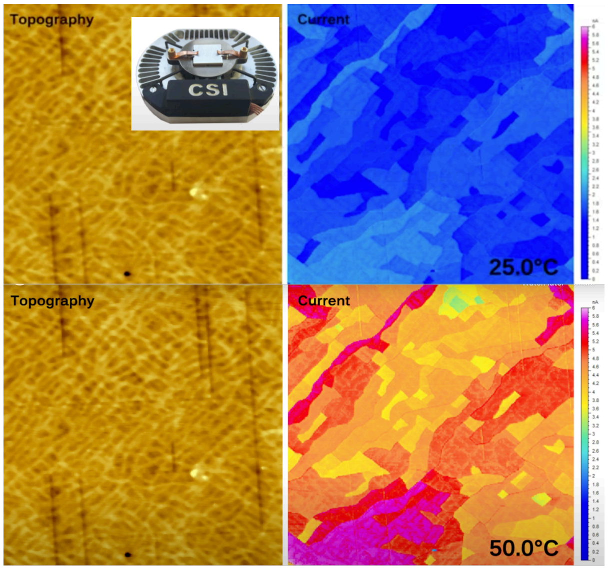


Fig.8 Topography (left) and current (right) of VO2 measured with heating accesory from 25 ºC (top) to 50 ºC (bottom). The inset shows a picture of the heating add-on device.

Figs. 8 (top and bottom) show a topography/current maps on a VO2 sample measured with Soft ResiScope for different temperatures. Heating accesory was used to perform a temperature ramp from 25 degrees upto 50 degrees at a speed ramp of 0.1 degree/minute. As it can be seen, position is highly stable and current maps show that VO2 domains increase the current from 100 pA to 6 nA. As described in previous sections, one of the advantages of ResiScope is that the user does not have to worry about changing de amplifiers setup. As everything is software controlled, temperature experiments do not require amplifier adjustment in case the current increases significantly. This example shows how ResiScope is capable of tracking changes of conductivity with high sensitivity (variations of 50 pA among grains) in a samples like VO2 where conductivity can change orders of magnitude as it approaches to the phase transition temperature.

You can find a video with more detailed images in https:/www.csinstrumwents.eu/videos

HD-KFM and ResiScope analysis of SRAM

Static Random-Access Memory (SRAM) is essential in high-speed and high-performance semiconductor applications. Advanced AFM techniques like (Soft) ResiScope and HD-KFM provide critical insights into SRAM's material properties like doping concentrations or fabrication defects crucial for optimizing SRAM design and manufacturing processes.

In Fig. 9 it is shown the topography image (left) and the surface potential measured with HD-KFM (right) on an SRAM device. Surface potential shows differences of only 30-50 mV between p-doped areas and n-doped channels and 300 mV with the n-well surface. Moreover, some of the cells show clearly defects in the SP map (highlighted in orange) which are not visible in the topography. Although SP values can be related with differences in carrier concentration levels, other techniques like Scanning Microwave Impedance Microscopy (SMIM) are more suitable to obtain quantitative values.

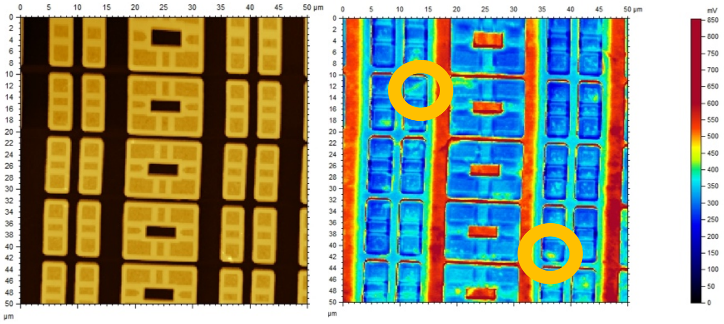


Fig.9 Topography (left) and surface potential (right) of SRAM measured with HD-KFM mode.

Another advantage of the Nano-Observer II AFM is the capability of combining HD-KFM and ResiScope without need to change anything in the setup or the cantilever. This is illustrated in Fig. 9 where both the curren SRAM of Fig. 8 are depicted.

As the sample is biased in ResiScope mode, it can also provide information about the device performance (1 volt in the image shown). The same defects highlighted in Fig. 10 show in the conductive maps normal performance in one case and defective in another (no difference in currrent between p-doped and n-doped).

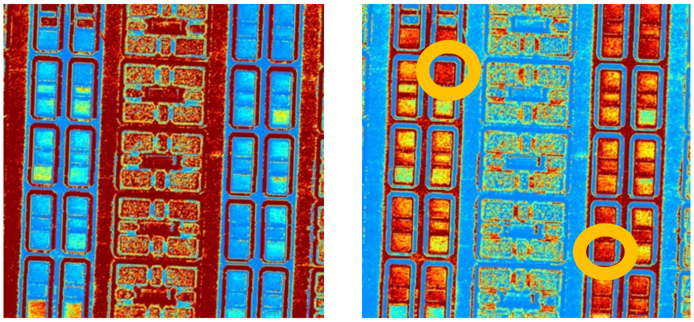


Fig.10 Current (left) and resistance (right) of SRAM measured with ResiScope.

This example highlights the benefits of using both techniques to obtain complementary information of the device. More over by using Soft ResiScope it is possible to perform conductive measurements with minimal damage due to the lack of friction

Another important need in the semiconductor industry is the characterization of the doping concentration as semiconductors show different electrical properties depending on both the quantity (carrier concentration) and the type of dopant (n or p). This knowledge helps to have a better understanding and control of the fabrication process.

Fig. 11 shows an example of a measurement on a cross-section of a silicon substrate with regions increasing levels of carrier implants (staircase type). Fig. 10 (top) shows the topography of the sample where polishing vertical lines are visible. Fig. 10 (middle and bottom) show the resistance map and its cross-section profile respectively. Each region has a size of 500 nm (lateral size) and it shows a decrease of the resistance (from right to left) regions ranging from 100 ohms to 1 Mohm. This shows the capability of ResiScope to be used to track differences in resistance in realtime with several orders of magnitude in difference (from 10^2 to 10^6 ohms) without loosing sensitivity.

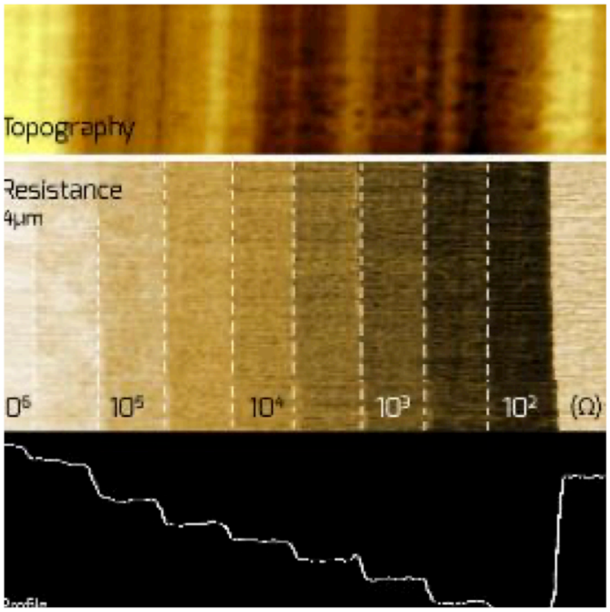


Fig.11 Topography (top), resistance (middle) and resistance cross-section of progressive dopant concentration in silicon measured with ResiScope.

Conclusion

The advanced AFM techniques offered by CSInstruments, such as Soft ResiScope, ResiScope, and HD-KFM, significantly enhance research outcomes in semiconductor analysis. HD-KFM provides high resolution imaging of surface potential as the software selects automatically the proper frequency around the second eigenmode to amplify the signal through the resonance. Resiscope and Soft ResiScope provides the largest dinamic range measurement of current/resistance without need to change the experimental setup when measuring both insulating and highly conductive materials. Soft ResiScope has the advantage of avoiding friction. These modes can also be switched by software without user intervention on the setup. This makes possible to measure the same area with different modes. In addition these modes are compatible with other modes like MFM and SMIM (see MFM appnote and ResiScope app note).