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MDM
Materiali e Dispositivi
per la Microelettronica

IMAGING P-N JUNCTIONS BY SCANNING NEAR-FIELD OPTICAL, ATOMIC FORCE AND ELECTRICAL CONTRAST MICROSCOPY

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In this work, results on local electrical characterisation of pn junctions, based on scanning probe microscopy are presented. These results are part of the experimental work achieved during the visit at Nanonics Imaging Ltd in Jerusalem, where near field optical techniques are being integrated with local electrical characterisation of materials. The results are compared with those obtained on similar samples using the Electric Force Microscopy.

Introduction

Scanning probe microscopies are very promising techniques for the local characterisation of materials. Of particular interest for microelectronics are those configurations, which can access the local electrical properties of materials and devices by scanning with a conductive probe and collecting through a system, which can simultaneously, display topographical features and electrical properties. Amongst the issues which can be addressed in this way, there are some of the most important topics of current microelectronics, such as: local capacitance measurements, small scale variations of dielectric constant and of resistivity, pn junction delineation, oxide quality and so on. Though the measurement set up is easy to be achieved in principle, difficulties arise when important topics such as quantification of results and optimisation of spatial resolution are to be covered. This is mainly due to the problem of modelling such local interactions where the unknown parameters are several, i.e., tip shape, contact area, range and nature of forces. Our laboratory started a collaboration with Nanonics Imaging Ltd, which is strongly committed with the development of characterisation techniques based on the integration of scanning near-field optical microscopy (NSOM) and electrical measurements. The group is also involved with the optimisation of these instruments. The collaboration was initiated by a visit to Nanonics during which measurements were tried on several kinds of samples, namely pn junctions, titanium silicides films, and thin thermal oxides, using combined NSOM and electrical measurements in various configurations.

In this report, results are presented regarding the delineation of pn junctions using an NSOM combined with electrical measurements. These results are discussed and compared with previous results obtained on similar samples using the Electric Force Microscope (EFM) already present in our Laboratory[1,2].

In the discussion that follows the presentation of results, particular attention is devoted in tracing the possible developments and perspectives of these techniques.

Sample preparation and experimental set up

The pn junctions used in this work are obtained from perimeter diodes present on a test pattern identified by A648. As shown in Fig. 1, the diodes have been cut and lapped in order to access the pn junction on the cross section. Pads are contacted to allow junction bias. Due to the preparation procedure, only one junction in every two can be contacted, while the other is floating. A n+/p device (S1) was used in the EFM experiments performed with the Topometrix Instrument presently in the Laboratory, while a p+/n device (S2), with the same geometry of the former, was measured with a Nanonics system. Both experimental set-ups are briefly described below.

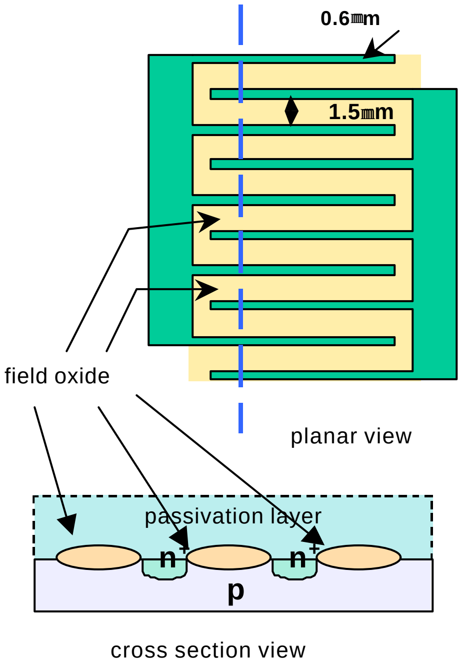

Fig. 1 Diagrammatic representation of the measured samples

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[1] Lidia Baccarini, graduation thesis, P.A.C.S. code 61.16, Milano, March 1999.

[2] G.Tallarida, L.Baccarini, S.Spiga, Imaging Pn Junctions by Electrostatic Force Microscopy, workshop on characterisation of materials and devices for microelectronics, Lecce 9-11 November 1998.

Fig. 2 A Nanonics near-field optical/AFM/electric probe

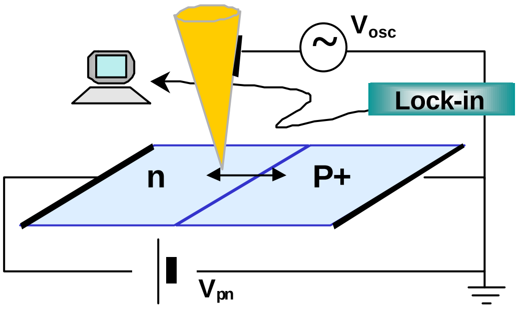

Fig. 3 Drawing of the EC signal detection set up in the Nanonics system

- *Nanonics system*

Measurements are performed using a Nanonics NSOM/AFM 100 mounted on the stage of an optical microscope and connected to an AFM/STM control system. The software resolution of images is 256 x 256 (points x lines). The probe used is a tapered optical fiber, covered by a layer of gold. The fibre is bent in order to resemble an AFM tip, as shown in Fig. 2. The radius of curvature of the probe apex is of the order of 100 nm.

The SPM system is operated in contact mode and the interaction between probe and sample is kept constant by a laser feedback, which acts on the topography signal. The NSOM signal is obtained in illumination mode, that is using the fiber to bring, in near field condition, the light from an Ar^+ laser (488 nm wavelength) and collecting the reflected signal in far field, through an avalanche photo-diode. The optical signal is collected simultaneously with the topography image. To access the electrical contrast (EC) of the sample, an oscillating voltage is applied to the circuit formed by sample and probe, while the junction is biased. The electrical signal is collected through a lock-in amplifier, which records the in-phase current flowing through the circuit. This signal enters the control system and choosing the proper time constants, is synchronised with the optical and the topography data and displayed along side.

Best results were obtained by applying the oscillating voltage to the tip and collecting the in-phase current signal from the junction. A scheme of this configuration is shown in Fig. 3.

- *Topometrix EFM*

In the EFM a conductive tip (typically a silicon tip covered with a layer of platinum) is scanned over a sample in non-contact mode. The EFM senses the electrostatic force between the conductive probe and the sample surface. By changing the probe/sample distance it is possible to discriminate between morphological features, whose forces have short range and hence are predominant at low distance, and electrostatic forces, as they have longer range and dominate at higher distance. The experimental set-up used in our measurements is shown in Fig. 4. For each point a measurement at the feedback point is recorded (topography); afterwards the tip is pushed back by a distance d and a second measurement (the EFM signal) is taken. Therefore, there is an exact spatial correspondence between topography and EFM image. The images reported have a resolution of 200x200.

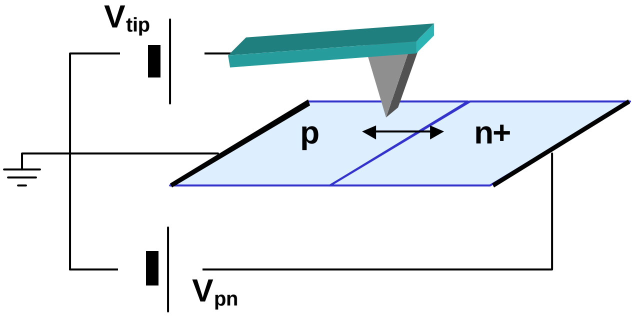

Fig. 4 Drawing of the EFM measurement set-up

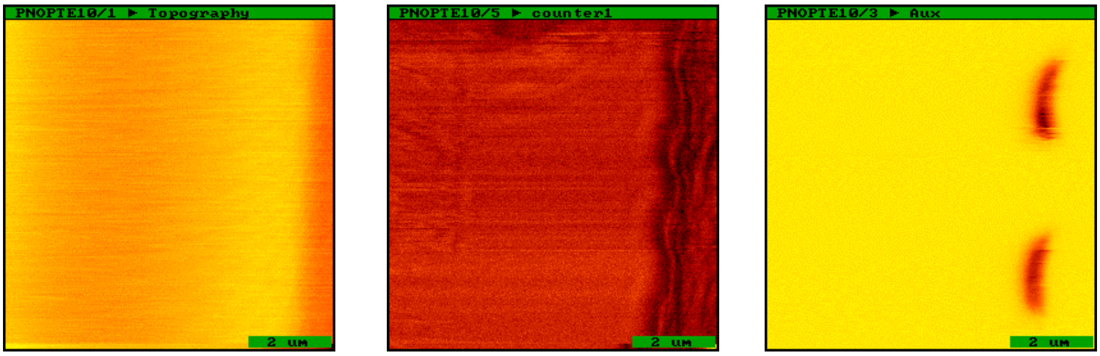

Fig. 5 Topographic (left), optical (centre), and EC signal (right) on S2 obtained with Nanonics system

Results

- *Nanonics system*

In Fig. 5 the topography, the optical, and the EC image taken simultaneously on the cross section of S2 are reported. The important parameters at which this measurement was taken are: scan area 8x8 μm^2; V_{pn}=5V; V_{osc}=50mV; ω_{Vosc}=100 kHz. The sample appears topographically flat. Only the edge between silicon and the passivation layer (the darker stripe on the right side of the left image) is evidenced. This step is also observed with standard AFM and it is due to the different erosion speed during the last step of the lapping process.

In the optical image different materials give different contrast and this allow to identify on the image the sequence of active areas and field oxide. The resolution of the image is strongly related to the sharpness of the focus of the optical signal on the collection lens.

The EC image clearly shows the two biased junctions. The darker areas are related to an increase of the collected current. By means of common image analysis software, the optical image and EC image can be combined together and cut around the area of interest, to give the images reported in Fig. 6. The two images come from two different measurements taken at V_{pn}=5V; ω_{Vosc}=100 kHz; V_{osc} is 50mV (Fig. 6, left) and 30 mV (Fig. 6, right). In both images, the area of enhanced electrical contrast (the darker spot) is placed just below the region where the p+ doped area is expected and its shape resembles that of the depletion region, although it appears larger than expected. Since a reverse bias is applied to the junctions, only the oscillating voltage applied to the tip induces the current flowing in the circuit. The depletion region acts as a capacitive area that induces the enhancement of signal in this region. Therefore, using such a configuration, we believe that the EC signal images the depletion region.

Time spent at Nanonics was not enough to further investigate the mechanism of the electrical contrast, however some measurements have been performed to analyse the effect of reducing V_{osc} and V_{pn}, respectively. For this purpose the same line, chosen so to cross a biased junction, was continuously scanned, while V_{osc} was changed. The same experiment was repeated varying V_{pn}. In Fig. 7 the line profiles obtained at V_{pn}=5 V and ω_{Vosc}=100 kHz, and varying V_{osc}, are displayed. The peak value of the EC curve decreases with V_{osc}, while the voltage applied to the tip does not influence the width of the high contrast area. It is remarkable to note that an oscillation amplitude as low as 30 mV

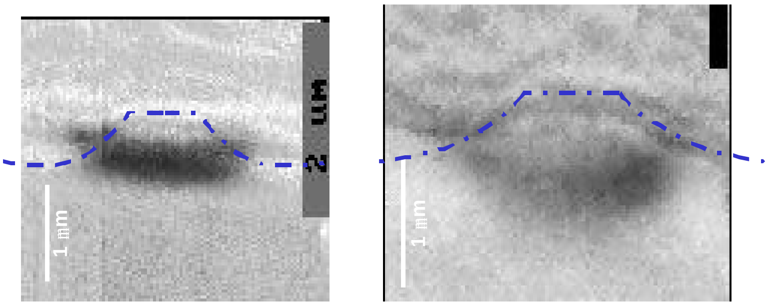

Fig. 6 Combined optical (left) and EC signal (right) in two different experiments

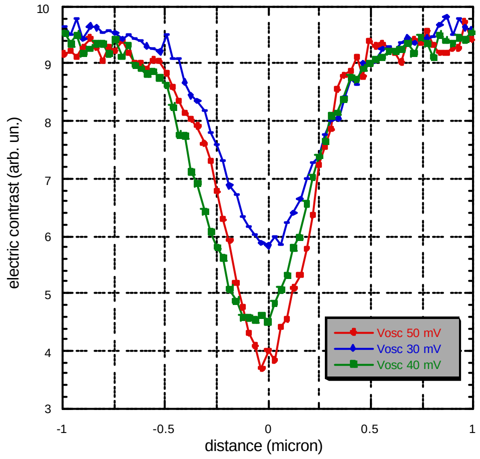

Fig. 7 EC signal of the same line as a function of V_{osc}

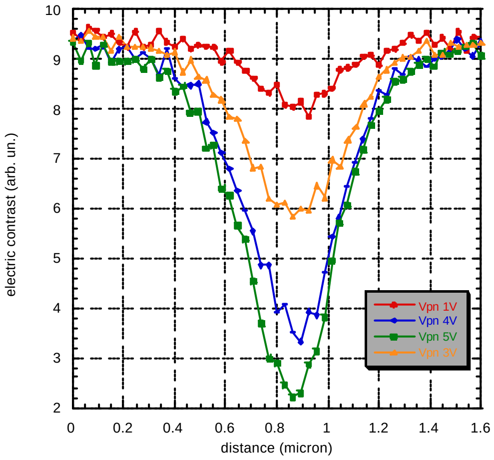

Fig. 8 EC signal of the same line as a function of V_{pn}

still gives a good contrast, as the use of low probe signals is to be preferred in order to reduce the effects of the probe on the measurements.

The line profiles obtained varying V_{pn} are shown in Fig. 8; other parameters are V_{osc} = 50 mV, ω_{Vosc}=100 kHz. The peak value sensibly decreases with V_{pn}, but again no sensible change in the width of the profile is registered. This suggests that the width of the line is determined by the sensitivity of the probe, and that the shortening of the depletion region with the decreasing of V_{pn} is invisible to the probe. Presumably, the radius of curvature of the particular probe used combined with the interaction volume induced by electric forces to generate an effective spatial resolution of 0.2 µm.

- *TopoMetrix EFM*

Fig. 9 shows the topography and EFM image obtained on sample S1. Relevant measurement parameters are V_{pn}=5V, V_{tip}=1V, distance from feedback point d = 50 nm. The topography shows a quite flat sample. The EFM image evidences the two biased junctions by an enhanced contrast between the n+ and the p region, though without a sharp definition of the two areas. However, some features, which are related with topography, are still visible on the EFM image, revealing that, at this probe/sample distance, there is not a reliable separation between topographic and electrical forces. The signal/noise ratio is quite high and in order to detect a good signal, V_{tip} had to be kept $\geq$ 1V. To investigate if the EFM signal is sensitive to V_{pn} variation, a single line (shown in the picture) was repeatedly scanned, while the reverse bias at the junction was varied. The results are reported in Fig. 10. There is a clear correlation between the line profile and V_{pn}, especially at high voltages: The electrostatic force signal is sensitive to potential variation on the surface and somehow follows the potential drop at the junction. However, this drop takes place in a region, which is 1 µm wide,

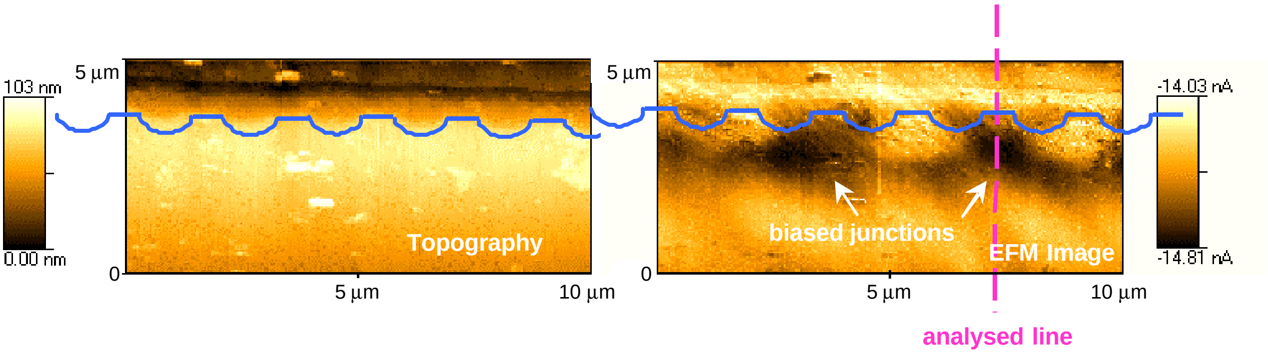

Fig. 9 Topography (left) and EFM image (right) of sample S1 obtained with the Topometrix system

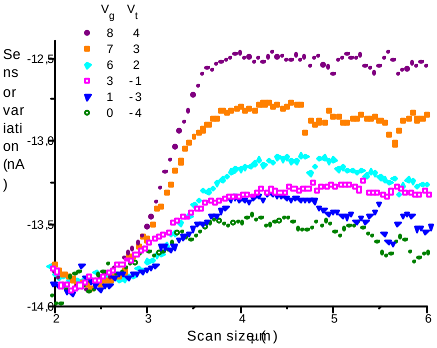

Fig. 10 EFM signal of the same line, as a function of junction bias

independently of V_{pn} and remarkably wider of the expected depletion region width. To explain this, two main factors are to be taken into account: V_{tip} is of the same order of magnitude of V_{pn} which means that the tip is not just probing the surface, but it influences the measurements with the generated electrostatic field; the total distance between probe and sample (d plus the non-contact distance) is of the order of 100 nm. In these conditions the interaction volume is probably quite large, and this might explain the reason of such a poor spatial resolution.

Discussion and conclusion

The two methods used to obtain an electrical contrast image of a biased junction are different in principle, since one is sensitive to the depletion region, while the other registers differences in electrostatic forces, which are connected to potential variation on the surface.

A positive result of detecting electrical signal from the probe, rather than forces, is that there is little intersection between topography and electric image, as well as an immediate correspondence between the two images, i.e. optical and electrical. Measurements performed using the lock-in amplifier allow very low probe voltages, and give a much better signal/noise ratio, if compared with the EFM experiment. Moreover, the possibility of detecting the optical signal allows a better definition of features associated with alterations in material properties and hence gives the possibility of overlapping meaningfully important material characteristics to the electrical image.

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