Recent progress and insights in two-dimensional carrier profiling using scanning spreading resistance microscopy.

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Abstract. In this paper, we present the overall progress in scanning spreading resistance microscopy (SSRM) capabilities, achieved over the last year, with respect to all aspects of the technique. Progress in spatial resolution (less than 3 nm) has been achieved by optimized sample preparation and the development of better hard conductive diamond tips. Limitations in tip (and sample) lifetime have been reduced by the introduction of a more sophisticated, damage reducing tip movement and pressure control procedures. Data interpretation has been improved by the introduction of automated quantification software and the development of a more advanced model for the diamond tip–semiconductor contact, including the impact of the surface states at the polished sample surface.

INTRODUCTION

As emphasized in the International Technological Roadmap for Semiconductors (ITRS), two-dimensional carrier profiling is one of the key elements in support of technology development. Scanning spreading resistance microscopy (SSRM) has since its conception been a very promising candidate for this purpose as it has an attractive spatial resolution, concentration sensitivity and a relatively easy first order quantification [1]. The latter has for instance led to the use of SSRM for doping profile engineering (halo, channel implants, ...), to study lateral diffusion effects in MOS-devices [2] and for the analysis of more recent devices such as fully depleted SOI-transistors [3]. Typical examples are shown in Fig.1. The data in Fig.1(a) are taken on a 90 nm NMOS-transistor and illustrate its ability to delineate the details of the source/drain extension as well as the (small) concentration variations within the channel resulting from the halo and Vt-adjust implants. The data shown in Fig. 1(b) are taken on a fully depleted SOI-transistor whereby the Si-layer thickness on top of the (thick) oxide layer is only 45 nm. Details of the dopant profile within the channel can again be resolved and related to the processing steps [3].

Bringing the performance of SSRM in line with the needs of next generation technologies implies that the spatial resolution should approach 1 nm with a high degree of quantification accuracy and sensitivity. This has necessitated a continuous effort in improving all the practical (sample preparation, tips, measurement procedures) and theoretical (data interpretation, calibration, physical modeling) aspects of the technique. The most important ones will be discussed in this paper.

FIGURE 1 (a) (left) SSRM measurement with full diamond probe of a 90nm gate NMOS transistor. Implant variations within the channel are clearly visible (b) (right) SSRM measurement of a 100nm gate FD-SOI transistor as obtained with a full diamond tip.
EXPERIMENTAL OPTIMIZATION

Improving the quality of SSRM (spatial resolution, noise level, reproducibility) has been based on three parameters: an improved sample preparation, a better probe tip and a new tip movement concept.

Sample preparation

Application of two-dimensional electrical characterization techniques based on Atomic Force Microscopy (AFM), usually requires measurements on the cross-section of the sample, making the sample preparation (cleavage and/or polishing) the first important step. Although SSRM is less sensitive to the sample surface than for instance scanning capacitance microscopy (SCM) [4], it has been found that better reproducibility and reduced noise level can be obtained with improved sample preparation. For instance, it has indeed been observed that a very flat surface enables a more stable contact and a drastic reduction of the force needed for a stable electrical contact. The latter is very important because high force is responsible for probe and sample damage and has a strong impact on the spatial resolution, probably because a lower force leads to a reduced “effective” tip radius.

In our optimized procedure, no chemical-mechanical polishing is used in order to avoid rounding effects and doping level sensitive polishing that may affect the results. All last polishing steps are realized with $\alpha_2\beta_3$ lapping films with decreasing grain size ending with a final polish using a 50 nm grain size. Aluminium oxide is preferred above diamond due to the fact that it is softer and reduces the presence of scratches. The typical RMS value provided with this sample preparation procedure (in the bulk and near the surface) lies between 0.2nm and 0.3nm. The use of this procedure allows stable current measurements for relatively low forces (expressed in terms of deflection set-point voltage values). Classical diamond coated probes (stiffness about 50N/m) typically give a stable electrical contact at about 1 or 2V versus 5V with the previous procedure.

A short HF exposure (a few seconds) just before the SSRM measurement also allows a small decrease of the force (about two times) but may introduce some topography artifacts and thus has to be used carefully.

Full diamond probes

At present most (commercially available) probes\(^1\) for SSRM are based on diamond coated silicon tips as the use of diamond has been shown to be essential to sustain the high forces used in SSRM [5]. Due to the final diamond deposition procedure, the outer surface of the tip is not flat but covered with sharp diamond crystals (see Fig. 2(b)). The electrical contact is realized through one of those grains. Note that, since contact is defined by the faceted diamond crystal, the effective “electrical” tip radius is better than the overall radius visible in the image in Fig. 2(b), and usually difficult to predict. Moreover the probability to have a multiple contact is not negligible. As the silicon tip itself has a rather high aspect ratio, cleavage of the tip due to the high shear forces exerted is frequently observed. Increasing the diamond film thickness can reduce this effect somewhat unfortunately at the expense of the tip radius as the thicker coating tends to become smoother (less sharply up pointing crystals) [6].

\[\text{FIGURE 2. (a) Molded pyramidal full diamond tip. (b) Diamond coated Si tip.}\]

In order to overcome these limitations, low aspect tips have been developed [5]. They are molded pyramidal tips and their outer diamond surface

\[\text{FIGURE 3. SSRM measurement across a 3.5 nm buried oxide (realized with a full diamond probe and a 50mV bias potential on the probe).}\]

\(^{1}\text{Probe = tip + cantilever}\]
(deposited first within the mold) is flat (see Fig. 2(a)). Recent improvements of this process [7], have demonstrated a significantly enhanced spatial resolution [3] [8]. For instance probing a 3.5 nm buried oxide layer (Fig. 3), still leads to a 10x increase in measured resistance which implies that the spatial resolution should be less than 3 nm [3] [8] [9]. With full diamond probes (stiffness about 40 N/m), a deflection set-point of 0.1 to 0.3V is sufficient for a stable electrical contact (compare with the 1 to 2V for classical diamond coated tips). This lower level (corresponding to a lower force) indicates that full diamond probes have a smaller tip radius (in order to maintain the same pressure) and thus a better spatial resolution.

Although they are superior in terms of spatial resolution, tip lifetime seems to be less as compared to the commercial diamond probes. Tip failures primarily occur due to small diamond grains being removed from the solid pyramid. Clearly improved diamond deposition is required leading to a stronger cohesion of the diamond film. Faced with these limitations in tip lifetime, it is imperative to limit the shear force i.e. providing a very well polished surface and working at very low force. The measurements also have to be done on small surfaces (a few square microns maximum) and at low speed to reduce the damaging of the probe.

**Pulsed-Force SSRM**

In order to reduce the destructive shear force during the high force SSRM scanning, an important new concept, the Pulsed Force SSRM, has been developed and implemented [10] [11]. Within PF-SSRM, the continuous movement of the probe at high force is replaced by a quasi multi-point contact mode (low force movement combined with high force measurement) leading to a drastic reduction of the probe and sample damage and hence to significantly longer lifetimes of both probe and sample (see Fig. 4).

**Probe and sample damaging**

One of the most important advantages pursued in this concept is the reduction in sample/tip damage. The success of that can be judged in Fig. 5 by comparing the surface damage induced by classical SSRM and PF-SSRM. In Fig. 5, a line scan through a topography image is shown where the sample was partly scanned in classical SSRM mode and partly in PF-SSRM mode. The reduction of the sample damage is clearly visible.

**FIGURE 4.** Comparison between SSRM (top) and Pulsed Force SSRM (bottom). The constant high force is replaced by a low force interrupted by short high force peaks. In PF-SSRM the electrical measurements in PF-SSRM is confined to the high force period, the topography measurement to the low force period. In SSRM both are performed simultaneously.

**FIGURE 5.** Topography section. The latter shows that the sample damaging is reduced when using PF-SSRM.

**FIGURE 6.** PF-SSRM picture (bottom) electrical, (top) topography of a 0.18 μm NMOS transistor.
With respect to probe damage a similar reduction is observed and cleavage of diamond-coated probes occurs far less frequently.

**Results on a 0.18 µm NMOS**

The PF-SSRM technique has been used on a 0.18 µm NMOS transistor (Fig. 6). The measurement was done with a full diamond probe. This experiment demonstrates that PF-SSRM is completely functional and provides the same sensitivity and spatial resolution as standard SSRM. It is, for instance, very easy to observe the LDD-structure. A very important asset of the PF-SSRM technique is the ability to collect extra information during the low force cycle. For instance in normal SSRM it was virtually impossible to obtain any topographic information as the tip was running continuously in high force contact with the sample which leads to a very poor topographic sensitivity. In PF-SSRM, the accompanying topography image can be taken in the low force cycle and thus provides extra information on the structural details of the devices and aids in determining the dopant registration (size of the gates, presence of nitride, silicided region, ...).

**QUANTIFICATION SOFTWARE**

One of the major advantages of the SSRM technique is the relative ease of quantification. In principle a straight conversion of spreading resistance (SR) to local resistivity ($\rho$) can be made using the ideal (flat, pure-ohmic contact) formula $R = \rho / 4a$ (where “a” is the tip radius). The latter already provides a reasonable accuracy. As in practice a true straight-line dependence is never observed, among others due to the influence of the contact resistance (also called the barrier resistance), the probe resistance and the back-contact resistance, data interpretation is usually based on a look-up procedure based on a calibration curve. Provided a high reproducibility is maintained this assures quantification accuracy as good as 20-30%. For very complex 2D-profiles, (small) additional corrections are necessary to account for the two-dimensional current flow induced by nearby conductive or insulating layers [12]. Finally as carrier profiles are measured effects like carrier spilling or the impact of surface states (on the polished surface) may cause some distortions in particular in lowly doped areas [13].

Efforts towards enhancing the data interpretation have concentrated on automating generation of the calibration curves as well as on software suited for the fast quantification of 1D and 2D profiles using these calibration curves. Physical modeling of the probe-semiconductor contact as well as of the polished surface has provided information on the potential distortions. Note that the latter is a universal problem not limited to SSRM but equally present with SCM and even with electron holography [14].

**Automatic generation of calibration curves**

In view of the large tip consumption, a fast evaluation and calibration of newly mounted conductive probes is a major issue.

A classical evaluation procedure of the probes consists in the acquisition of calibration curves constructed by collecting the resistances measured for different homogeneous calibration samples with a well-known resistivity (for each impurity type).

Whereas originally separate samples of different resistivity levels were used to establish the calibration curves (5-6 for each impurity type), dedicated epitaxial test-structures (one for each type) with a 1D staircase-structure are now used to obtain a complete calibration curve from a single scan. [15]. Obviously, the latter reduces drastically the time required to establish a calibration curve. In these structures, the resistivity levels are ranging from 1e-3 to 10 Ω·cm (corresponding to the concentration range of interest) and have been calibrated with the Spreading Resistance Probe technique (SRP) and Secondary Ion Mass Spectrometry (SIMS). In view of the limited lifetime of the tips and large dimensions of the present calibration structures, efforts are on-going to develop a second generation with much thinner layers thus limiting the amount of scanning for the collection of a full calibration curve.

In order to eliminate the manual extraction of the resistances corresponding to each staircase step a dedicated program, called MicroQuanti, (written in Visual C++) was developed to automatically build the calibration curves based on the raw data collected for the staircase calibration-structures.

**Automatic quantification for 1D and 2D carrier profiles**

A fast and very easy way to obtain resistivity profiles from the raw resistance data is to use a calibration procedure. In such a procedure, the resistance profile of the unknown sample is measured with the same probe and, using linear interpolation on
PHYSICAL MODELING

In order to increase the quantification accuracy, especially at lower concentrations (<1e17 at/cm³), a detailed physical model for the tip-sample and the surface has been developed. The latter has been necessary to explain some discrepancies between experimental and theoretical carrier profiles and the impact of the measurement bias on the measurement results.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Surface States</td>
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<tr>
<td>Zero-level</td>
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<tr>
<td>SS concentration</td>
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<td>Schottky barrier</td>
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<td>( E_b = e\phi_m - e\chi )</td>
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<tr>
<td>Tunneling distance</td>
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</tr>
<tr>
<td>Contact Size</td>
<td></td>
</tr>
<tr>
<td>Tip radius</td>
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</tr>
</tbody>
</table>

**Limitations of cross sectioning**

One of the most interesting capabilities of the SSRM technique is its ability to locate accurately the electrical junction position due to the presence of a clear resistance peak at that location. As SSRM is probing the (mobile) carrier distribution and not the dopant distribution, this resistance peak corresponds to the location of the electrical junction not the metallurgical junction (as determined by SIMS). One profile can be extracted from the other one through a solution of the Poisson equation [17]. For typical (highly doped) source/drain-well structures, the SSRM resistance peak corresponds very well to the theoretical electrical junction position for a particular dopant profile.

However one should remain cautious of the intrinsic assumption of SSRM (and many other techniques relying on sample cross sectioning, SCM, EH,…) that SSRM probes the near-surface carrier profile on a cross sectional surface. If the sample preparation procedure in itself would cause any change/disturbance in the carrier profile, this will inevitably lead to an apparent error in the SSRM results. Such a disturbance could, for instance, be caused by surface...
charges, surface states, Fermi level pinning, as a result of the (mechanical) sectioning procedure. An extreme case of such a disturbance can be observed when a focused ion beam (Ga) is used for the sample sectioning. In that case the ion solid interaction will lead to Si-amorphization while the Ga-incorporation may lead to a p-type concentration as well.

Even with the standard mechanical polishing techniques, evidence for such an interaction can be found on structures consisting of lowly doped and/or low gradient junctions which are particularly sensitive to surface interactions. A large shift of the SSRM electrical junction position towards the surface can be seen for p+n structures as compared to the expected theoretical bulk electrical junction position (also called zero-field position) [17] or even a complete disappearance of the junction peak for n+p structures (see Fig. 8 for the p++n I10 structure and Fig. 9 for the n++p I12 structure). The latter is not a measurement artefact of SSRM but clearly an effect caused by the cross sectioning procedure.

In view of those observations it has been necessary to introduce a more elaborate model for SSRM whereby one includes the effect of the surface preparation and the impact it may have on the internal carrier distribution (and thus the SSRM measurement) and the tip-semiconductor contact. The proposed model is based on a Schottky-like contact with tunneling and surface states describing the surface modification [13] [18]. A set of parameters (to calibrate the model) has been chosen based on literature standards and on initial experiments (see table 1). ISE/DESSIS device simulations have been performed to evaluate and refine the model.

**Evaluation of a new contact and surface model**

One of the most important points in the proposed model is the recognition that on the polished surface (as on any surface) the situation is far from ideal and many surface states can be present. Moreover the contact is not really ohmic but more schottky-like with a tunneling barrier. In highly doped areas, the effect of surface states (SS) is negligible and the barrier is transparent, causing the contact to be almost ohmic. In that case the interactions are minimal and excellent agreement between SSRM and the expected electrical junction can be observed.

The importance of this model is clear when looking at the simulation results for the lowly doped, low gradient p+n and n+p I10, I12 junctions discussed in Figs. 8 and 9.

The samples I10/I12 have been analyzed previously in a detailed SIMS-SRP calibration study and are very well characterized [17]. Starting from the SIMS profile, the ISE/DESSIS device simulator was used to calculate the SSRM-response as a tip moves along the cross section of this sample. In the simulations the effect of the surface states and the detailed contact description is included. The curve with all the simulated spreading resistances for the different lateral positions gives the simulated SSRM profile (to be compared to the experimental results in Figs. 8 and 9). To reduce the calculation time, we have
performed two-dimensional simulations (and not 3D). This has no influence on the junction position (our main concern here) but only on the absolute resistance levels. Hence a quantitative comparison of the calculated resistance values is not possible.

Sample 110 is a p-type (B) implant (>10^{20} at/cm^{3} at the surface) on a n-type (As) substrate (4.10^{14} at/cm^{3}). In Fig. 8 we may observe that there is a very good qualitative agreement for the junction position between the model and the experimental profiles. We observe the same drastic shift of the junction peak towards the surface as compared to the zero-field position in both cases. The apparent junction displacement is a result of the influence of the surface states, which cause an accumulation for lowly doped n-type, and an inversion for lowly doped p-type. That is due to the fact that for a small n-type doping, the Fermi-level is initially below the SS zero-level, thus causing a bending of the conduction band towards the Fermi-level. The net results is that one experiences a large bending of the electrical junction position towards the original surface resulting in a much shallower junction position on the cross-sectioned surface.

Sample 112 is a n-type (As) implant (>10^{20} at/cm^{3} at the surface) on a p-type (B) substrate (2.10^{15} at/cm^{3}). Once again, the very good qualitative agreement of the model with the experiment is evident (see Fig. 9). The junction peak is now absent in both cases and is replaced by a slow gradual increase of the resistance with depth. Again the latter can be understood by an inversion layer induced by the surface states along the cross-section in the p-type region. The electrical junction does not intersect the cross-section surface of the sample anymore and thus cannot be detected. The disappearance of the junction due to surface states results from the inversion they induce in the lowly doped p-type region. For p-type, the Fermi-level is indeed below the SS zero-level causing a transfer of electrons from the surface states to the bulk. Because of the low doping level in the bulk and because of a SS zero-level at 0.28eV above the midband energy, we have a large depletion layer. Bands bend enough so that conduction electrons become the majority carriers near the surface and form the inversion layer.

This new model offers a better physical understanding of the contact and the surface. It allows a deeper comprehension of the influence of the sample preparation and of the probe-silicon sample contact. Further details and illustrations concerning this model are to be found in [13]. It should be noted here that these phenomena are present with any technique using a cross sectioning procedure including SCM and even electron holography. The impact of the surface states is of course closely linked to the concentration levels. As such the disturbances observed in Fig 8 and 9 are usually not observed when probing source/drain – well junctions (the most common applications for 2D-profiling techniques) and only apparent for profiles like source/drain or well-substrates junctions.

CONCLUSIONS

Recently the spatial resolution of SSRM has been improved till below the 3 nm level. The latter is a result of a refined sample preparation procedure (maximal roughness less than 0.3 nm RMS) and improved tip quality. It is shown that solid pyramidal diamond tips are superior in terms of spatial resolution although improvements in lifetime still are required. Enhanced tip and sample lifetime are expected from the new measurement concept (PF-SSRM) whereby the lateral shear force is drastically reduced. Routine quantification based on automated look-up on calibration curves is now available providing reasonable accuracy. The applications presented (halo engineering, SOI structures,..) all demonstrate the strong points of SSRM i.e. spatial resolution, quantification and concentration sensitivity. Finally, insights in the physics of the contact and the polished surface have been achieved addressing potential disturbances for lowly doped profiles.

ACKNOWLEDGMENTS

P. Eyben is indebted to the Flemish Institute for Support of Scientific Research (IWT) for his Ph. D fellowship.

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