Beyond SRP: Quantitative carrier profiling with M4PP

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Understanding dopant diffusion and activation mechanisms is a key issue for future sub-45 nm CMOS technologies. This understanding requires the availability of accurate chemical and electrically active dopant profiles. In this work we will focus on the accurate and reliable characterization of carrier depth profiles for ultra-shallow (USJ) structures. Typically conventional means such as Spreading Resistance Probe (SRP), which uses two high-pressure probes (10 GPa) with a contact radius of about 1 μm and a separation of 30 micron, are running out of steam in the sub-30 nm depth regime. This is mainly due to the need to apply for multi-layer structures quite large Laplace-based deconvolution correction factors (> 1000) on the raw data causing excessive noise amplification. These correction factors can be circumvented by performing a series of microscopic four-point probe (M4PP) measurements along a beveled sample with a small enough angle (few minutes). In M4PP, the probe tips make an elastic (non-penetrating) contact with a 1.5 μm pitch leading to an enhanced dynamic range because of the reduced sampling size and penetration. Subsequently, the underlying resistivity and carrier depth profiles can be easily extracted by the simple calculation of the differential sheet resistance for each of the sub-layers. Results of this new technique will be illustrated for a series of CVD (Chemical Vapor Deposition) grown box profiles and will be compared with more conventional approaches.

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Introduction

Obtaining reliable active dopant depth profile information continues to be a crucial issue as technological CMOS dimensions keep shrinking [1]. It is well known that conventional carrier profiling techniques such as the Spreading Resistance Probe (SRP) are no longer reliable for sub-30 nm structures [2], among others because of the large probe contact radii used and therefore the quite large correction factors needed to deconvolute the underlying physical profile information. Other promising techniques which recently have emerged (using 100 times smaller contacts) such as Scanning Capacitance Microscopy (SCM) [3] and Scanning Spreading Resistance Microscopy (SSRM) [4] either do not have the required electrical resolution (SCM) [5] or need appropriate calibration and contact modeling to extract the underlying profile (i.e. are relative techniques) [6]. In this work we will explore the capabilities of an alternative absolute technique, i.e. differential sheet resistance carrier profiling based on micro four-point probe (M4PP) measurements [7] with a tip separation of 1.5 μm along a beveled surface.

Differential Sheet Resistance profiling

The basic principle of differential sheet resistance profiling is quite simple. One measures the sheet resistance ($R_{s,j}$) of a junction isolated layer at different depth positions (x_j). A higher index refers to a deeper depth position. In this work this has been achieved through the usage of a beveled surface using the procedures routinely used in qualified SRP operation [8]. As the depth increases, the theoretical sheet resistance of the (remaining) layer above the junction increases monotonically. Consequently the sheet resistance of a single sub-layer $\Delta R_{s,j}$ between depth positions x_j and x_{j+1} is given by (assuming parallel conduction through the sub-layers):

$$\Delta R_{s,j} = \frac{R_{s,j+1}.R_{s,j}}{R_{s,j+1} - R_{s,j}} \qquad (1)$$

If one assumes a constant resistivity ρ_j for each sublayer with thickness $d_j = x_{j+1} - x_j$, then the unknown resistivity can readily be obtained from:

$$\rho_j = d_j.\Delta R_{s,j} \qquad (2)$$

Assuming a flat bevel surface, the layer thickness d_j can be obtained from the lateral step size z_j and the bevel angle θ from:

$$d_j = z_j \sin(\theta) \qquad (3)$$

Finally, one can obtain the carrier density from the resistivity by applying appropriate mobility information. Obviously, the theoretical attractiveness of this approach is its simplicity. If one can perform a localized measurement of the sheet resistance, there is no longer a need to rely on complicated contact models and/or calibration procedures, i.e. this approach has the virtue of being an absolute carrier depth profiling technique.

To obtain a localized four point measurement, i.e. a small sampling volume or spotsize, the tip separation should be as small as possible, preferable only a few micrometers.

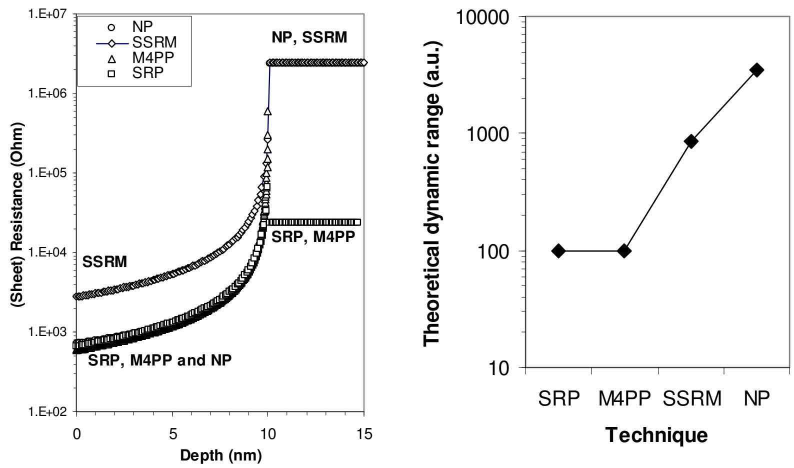

Figure 1: (a) Theoretical dynamic range M4PP, SRP, SSRM and NP (NanoProfiler) for $2x10^{20}$ at/cm^3 doped box profile of 10 nm thickness (sheet resistance of 625 Ohm/sq), (b) Ratio of highest vs lowest resistance for each technique.

An important issue to consider is the expected dynamic range of the raw data for a given dopant profile, which relates to the size of (implicit) correction factors that will be needed to extract the underlying profile (which also relates to the raw data noise sensitivity). Figure 1 compares the expected raw data dynamic range for a 10 nm, $2x10^{20}$ /cm^3 doped box profile for respectively M4PP relative to conventional SRP, SSRM and the NanoProfiler (NP) concept [2]. It follows that the (theoretical) dynamic range of M4PP is actually comparable with that of SRP, and is smaller than respectively for SSRM and NP. This relates to the fact the SRP data for such thin structures are indeed dominated by the sheet resistance of the involved layer. On the other hand M4PP differential sheet resistance profiling has a number of important advantages over SRP, i.e. goes beyond SRP. These are among others its virtual zero-penetration properties (see comparison with other zero-penetration tools [9]) and the fact the tedious SRP probe conditioning procedure can be skipped completely. The former issue will in practice actually result for sub-20 nm structures (on junction isolated layers) in a better dynamic range than SRP (which has a 5-10 nm penetration).

Experimental setup

In order to make the differential sheet resistance approach work in practice, one needs to be able to measure the sheet resistance in a sampling volume which is as small as possible, i.e. with very small four point probe tip separations. The micro four-point probe (M4PP) sheet resistance measurements were performed on a microRSP tool at Capres A/S. The microRSP tool is a commercial micro four-point probe system capable of electrical characterization of metal and semiconductor thin films with high spatial resolution [10]. The key part is a micro-fabricated four-point probe (see Figure

2b) which consists of four collinear equidistant metal coated SiO_2 cantilevers extending from the edge of a supporting silicon chip [7]. In the present work probes with a pitch of 1.5 µm were used. The individual cantilevers of the probe are 10 µm long, 750 nm wide and have a spring constant of 20 N/m. The contact size is 50-100 nm in diameter and the load is ~0.3 mg.

By use of the optical microscope the sample is positioned such that the tips of the four cantilevers are parallel to the bevel edge (Fig. 2a). Prior to the measurement on the bevel, a few measurements on the original wafer surface were performed. To obtain a sheet resistance profile, the resistance measurements start before the bevel edge (on the non-beveled surface) and continue along the bevel to the junction position, where the sheet resistance will be the largest. The beveled surface roughness as measured by Atomic Force Microscopy (AFM) was found to be around 1.5 nm RMS.

During the measurement the current set point was adjusted according to the measured resistance range. For sheet resistances higher than 10 kΩ/sq., the current was set at 1 µA; for resistances lower than 1000 Ω/sq., a current of 50 µA was used.

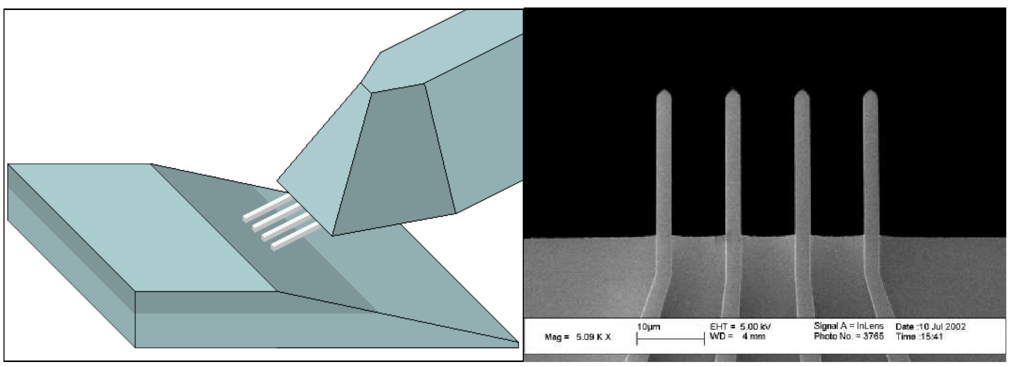

Figure 2: (a) Experimental setup M4PP, (b) M4PP probe configuration.

In a recent intercomparison of the accuracy of zero-penetration sheet resistance tools on Boron doped CVD layers on a medium doped underlying layer [9], it has been found that M4PP performs very well down to 10 nm thick layers, i.e. the impact of substrate shorting due to probe penetration is indeed negligible.

The depth resolution in this work is limited by the bevel angle used and the lateral scan step size during the sheet resistance data collection along the bevel surface. The angles used were in the range of 3-6 minutes, and the typical step size was 2 µm, which relates to a raw data depth resolution of about 1.5-2.0 nm. In principle a step size of 1 micrometer (or less) is possible in the future, i.e. a less than 1 nm depth resolution, but this will need some further optimization of the experimental setup (position error quantification and reduction/avoidance of the lateral movement of the probes when they touch the surface).

Data treatment

Although the extraction of the underlying active dopant profile from the M4PP sheet resistance versus depth raw data is in principle straightforward as discussed above, this approach is very sensitive to noise problems. The latter can originate from (i) surface roughness, (ii) higher order bevel rounding, (iii) positioning error and/or (iv) lateral 3D current flow. In order for equation (1) to work, the sheet resistance profile must be monotonically increasing. If this is not the case, due to some noise on the raw data, the deconvolution of the underlying profile becomes impossible. Even if the raw data are monotonically increasing the final carrier profile can have a quite oscillatory behavior in the absence of any smoothing. This is illustrated in Figure 3, which shows the raw data collected on a 58 nm thick junction isolated boron doped CVD layer. Although the visible raw data noise level on this measurement is quite low the corresponding carrier profile shows an oscillatory behavior. Hence, a well adapted smoothing scheme is mandatory. Here, we have chosen for the constraint cubic spline (CCS) algorithm [8], which is well known for its superior capabilities in the smoothing of SRP raw data. For practical reasons all data have prior to the application of the smoothing scheme, been interpolated equidistantly (on resistance log scale) with a lateral step size of 1 micrometer. As illustrated in Fig. 3b, the smoothed carrier profile shows much less oscillations now. Nevertheless, one can sometimes still observe minor oscillatory behavior near the CVD growth interface (Fig. 7b). Although, CCS controls the sign of the second derivative (convexity/concavity constraints) apparently this is not always sufficient. Hence, an even more sophisticated smoothing scheme controlling the third derivative or an alternative approach based on the maximum entropy method [11] may be needed to improve further the present results (see also further on).

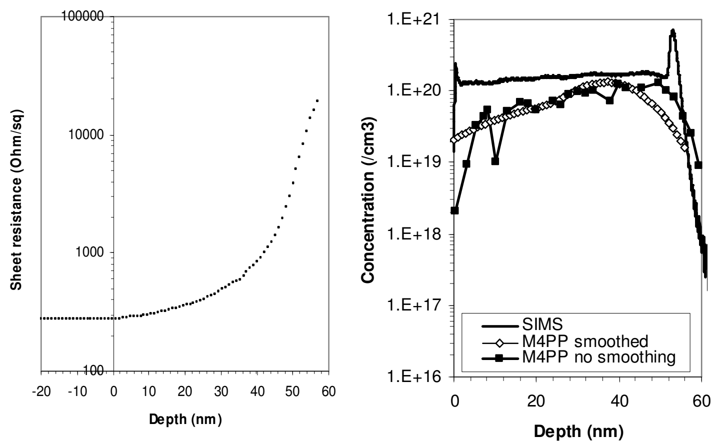

Figure 3: (a) Raw data and (b) M4PP carrier profiles with & without smoothing for 58 nm Boron doped CVD layer (also SIMS profile is shown).

Based on the smoothed raw data, the resistivity calculation starts at the deepest point (at the junction) and proceeds upward towards the surface. Determining the starting point of the depth profile (depth zero) on the small angle bevels used here has proven to be still somewhat of a problem with the M4PP tool. Approximate starting points can be determined, but for the exact starting point we have in this work relied on the layer thickness as measured by Secondary Ion Mass Spectrometry (SIMS). Once the resistivity versus depth has been extracted the carrier levels have been determined using standard crystalline mobility models [12].

Bevel rounding

One can note in Fig. 3b that there is a steady decrease of the carrier level towards the surface in the first 25 nm. As this decrease has also been noted on other similar structures with different thickness (Fig. 7b) also with different origins, this is probably an artifact. To investigate this more closely, a detailed analysis has been made of the shape of the bevel surface near the edge, i.e. in the first 40 nm (with a Veeco WYKO 3300 optical profilometer). As can be seen from Figure 4a, there is indeed a non negligible amount of bevel rounding in the first 25 nm. To verify further this issue, a sheet resistance depth profile has been simulated for a perfect box profile in the presence of bevel rounding (as shown in Fig. 4b), and subsequently the carrier profile has been extracted backward neglecting the bevel rounding, i.e. assuming a perfectly flat bevel surface. As can be seen in Fig. 4, we indeed obtain the experimentally observed fall off of the carrier profile near the surface.

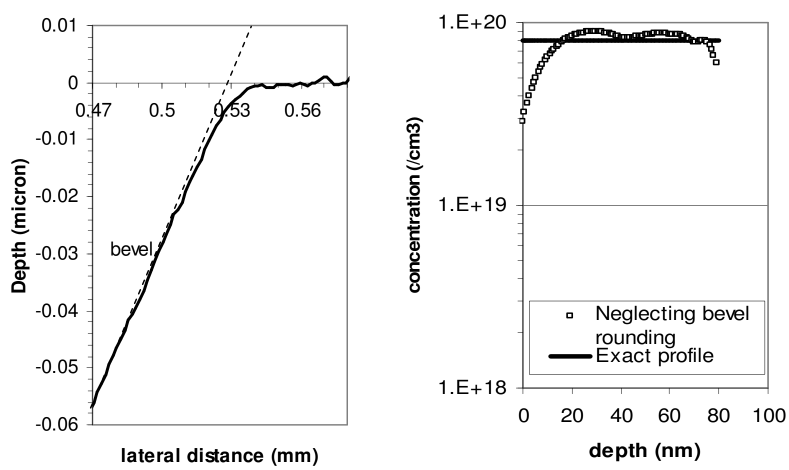

Figure 4: (a) Bevel edge rounding, and (b) impact on M4PP carrier profile.

Although at first sight this looks as a complication as one will need to find a way to measure simultaneously with the sheet resistance also the shape (topography) of the beveled surface (as can be done by AFM based systems), it is at the same time a nice illustration of the high sensitivity of the M4PP technique. Once bevel rounding can be taken into account properly, one can further reduce the noise levels on the raw data (sheet resistance versus depth) by using polishing techniques (as applied in SCM, SSRM) which result in a lower bevel surface roughness than conventional SRP beveling but are known to make bevel rounding worse.

Alternative issues might also play a role in the near surface rounding, such as the finite spotsize (sampling volume) of the probes. If one is contacting more lowly doped material close to more highly doped material positioned closer to the surface, the resistance of the deeper (more lowly doped) layer may appear lower than it actually should (due to lateral 3D current flow [13]), hence distorting the shape of the raw data curve and therefore also its quantification.

Discussion

Now that we have discussed the overall procedure for obtaining differential sheet resistance based carrier depth profiles, let us take a look at a few particular issues into more detail, such as reproducibility, sensitivity, depth resolution and quantification.

Figure 5 shows the raw data for different measurements on the same structure and the corresponding extracted M4PP carrier profiles. This illustrates a good reproducibility is feasible within 10 %. It should, for completeness, be mentioned that there are still some lifetime problems with the probes (max. of 100 data points) which need further work.

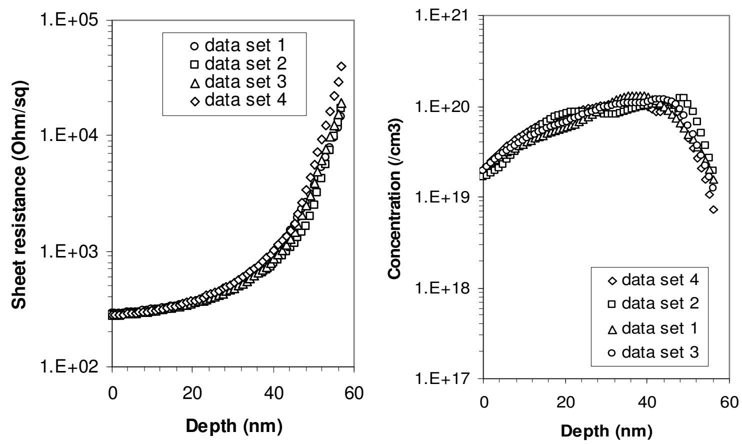

Figure 5: Repeatability of M4PP on 58 nm CVD structure: 4 measurements,(a) raw data and (b) carrier profiles.

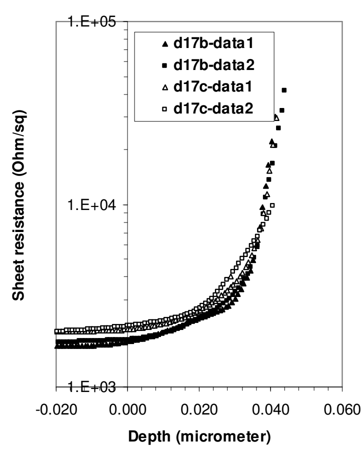

Figure 6: Sensitivity of M4PP: Raw data as obtained on the center piece D17c and border piece D17b of the same CVD grown layer (each two measurements). Smoothed data shown.

The sensitivity of the tool is further illustrated (besides the impact of the bevel rounding) by the measurements of a center and border sample taken from the same CVD grown wafer which was not as uniform as intended. As indicated in other work

[9] the non uniformity was about 50%, giving a higher sheet resistance for the center piece of the wafer. Fig. 6 illustrates that the M4PP sheet resistance depth profile is indeed able to resolve these differences.

As already mentioned part of the oscillatory behavior near the interface is probably smoothing related (Fig. 7b). However, in this particular case also part of the profile, i.e. the first bigger oscillation nearest to the interface, might actually be real, as it is also present in the SIMS profile. Further work will be needed to definitely determine this.

Furthermore, structures with different thickness have been investigated, down to 20 nm Boron doped CVD layers. Some of the obtained profiles are shown in Fig. 7. Despite the problem with the bevel rounding and the still somewhat limited raw data depth resolution (artificially enhanced here through interpolation), it is already possible to reasonably resolve the 20 nm thick layer. Recall that obtaining this result is based on an extremely simple mathematical procedure (apart from the smoothing) opposite to for example SRP, where very large correction factors (Schumann-Gardner) would have been needed to achieve a similar result.

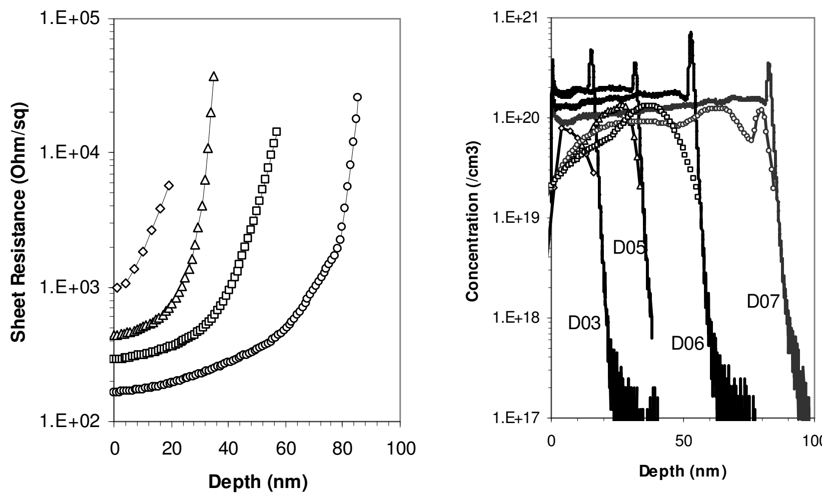

Figure 7: (a) raw data and (b) M4PP carrier profiles (markers) vs SIMS profiles (single line) for different CVD layer thickness.

Finally, to get a better idea of the potential capabilities of M4PP carrier depth profiling to existing alternatives such as SRP, SCM and SSRM, one sample has been measured with all of these techniques. Some of the raw data and all of the carrier profiles are shown in Fig. 8. It follows that the M4PP carrier profile (making abstraction of the bevel rounding issue discussed above) is in very good agreement with SIMS, SRP and SSRM. Note that, as already indicated above, the experimental raw data of SRP and M4PP look very similar. As both resistivity (from M4PP and SSRM) and direct carrier information (from SCM) were available, also the corresponding mobility of the layers could be determined to be in the range 60-100 cm^2/Vs. The crystalline mobility value for $1.5x10^{19}$ at/cm^3 p-type material is about 62 cm^2/Vs, which is in reasonable agreement.

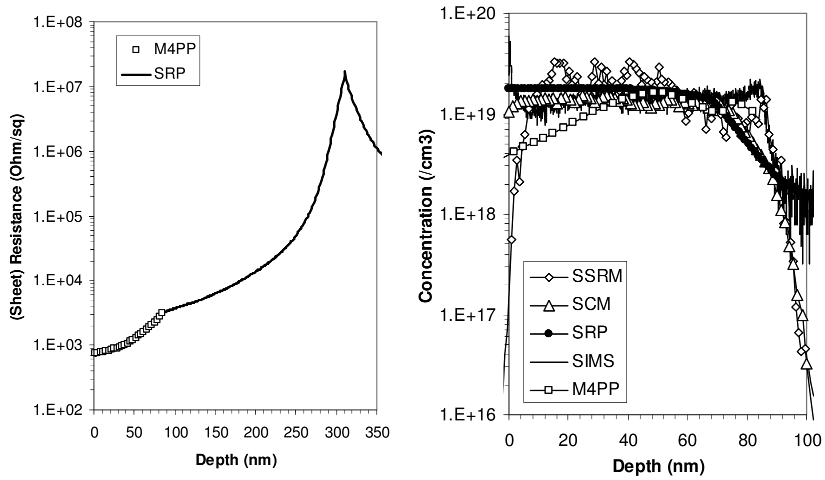

Figure 8: (a) Raw data and (b) comparison M4PP carrier profile with SRP, SCM, SSRM and SIMS for $p^{++}.p^{+}.n$ structure (right figure only show the p^{++} part).

Conclusions

There is still a growing need to get reliable carrier depth profile information as new technological processes need to be optimized. Due to its small four point tip separation of about 1 µm, M4PP can perform very localized sheet resistance measurements along a beveled surface with virtually zero-penetration, hence resulting in a sheet resistance versus depth profile. From these raw data, one can extract, through an extremely simple calculation procedure, the underlying resistivity (and carrier) depth profile, without the need for any calibration or modeling, i.e. differential sheet resistance is an absolute technique.

It has been illustrated that provided one uses a powerful smoothing algorithm one can obtain (in principle within one hour) useful carrier depth profiles with a good reproducibility and sensitivity down to 20 nm. The main (hardware) improvements needed are an increase of the probe lifetime (more than 100 points), reduction of the lateral probe step size (avoiding lateral tip movement), usage of improved bevel polishing techniques (as already used in SSRM) and the in situ measurement of the bevel rounding.

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