A COMPARATIVE STUDY OF SIZE DEPENDENT FOUR-POINT PROBE SHEET RESISTANCE MEASUREMENT ON LASER ANNEALED ULTRA SHALLOW JUNCTIONS

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In this comparative study we demonstrate the relationship/correlation between macroscopic and microscopic four-point sheet resistance measurements on laser annealed ultra shallow junctions (USJ). Micro-fabricated cantilever four-point probes with probe pitch ranging from 1.5 µm to 500 µm have been used to characterize the sheet resistance uniformity of millisecond laser annealed USJ. We verify, both experimentally and theoretically, that the probe pitch of a four-point probe can strongly affect the measured sheet resistance. Such effect arises from the sensitivity (or “spot size”) of an in-line four-point probe. Our study shows the benefit of the spatial resolution of the micro four-point probe (M4PP) technique to characterize stitching effects resulting from the laser annealing process.

INTRODUCTION

Maintaining adequate device performance within the continued miniaturization of semiconductor devices, necessitates the development of extremely shallow (<20 nm) source/drain extensions with very high dopant concentration and electrical activation level (1). As the millisecond annealing process used for ultra shallow junction (USJ) formation today only leads to partial (metastable) activation, one can no longer assume 100% activation. Thus, the dopant profile is no longer a good measure for the electrically active carrier profile, and secondary ion mass spectroscopy (SIMS) profiles can not accurately predict the sheet resistance, which is of utmost importance. Sheet resistance measured with conventional four-point probes has for many decades been used to characterize the doped region. However, conventional four-point probe measurements are seriously hampered by probe penetration leading to excessive sampling of the underlying substrate (2). Hence alternative approaches for characterization of sheet resistance are presently being investigated based on optical tools, non-contact measurements or four-point probe systems with drastically reduced probe penetration (2). The micro four-point probe (M4PP) technology developed at MIC (3) and Capres A/S (4) has proved to be a possible candidate to measure the sheet resistance of ultra shallow junctions (USJ) as it provides an evaluation of the sheet resistance without the artifacts of probe penetration. Moreover its drastically reduced electrode separation enables the analysis of sheet resistance variations on a much finer scale than feasible previously.

In this work, the M4PP was used to probe the lateral sheet resistance uniformity of laser annealed junctions. Periodic features related to the stitching overlays of the laser beams as well as non-uniformities within the laser beam itself can be clearly resolved. Using probes with various dimensions, the probe pitch effects on these measurements could be clearly resolved. A theoretical interpretation of its smoothening effect and the role of the actual measurement configuration are presented.

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EXPERIMENTAL

In this study an ultra shallow junction was formed by low energy ^{11}B implantation (0.5 keV, 1e15 cm^{-2}) into a lowly doped 300 mm n-type Si wafer and subsequently laser anneal. The laser anneal aimed at a nominal anneal temperature of 1300°C, resulting in a junction depth of 20 nm @ 1e18 cm^{-3}. The laser beam was scanned in straight lines across the sample surface with a step size of 3.65 mm whereas its spot size is significantly larger (~ 11 mm) such that the scanned lines overlap and each region gets irradiated several times.

To avoid a contribution from probe penetration, conventional four-point probes were not used for comparison in this work and all results were obtained with M4PP (Capres) and similar cantilever probes. These four-point probe MEMS devices consist of micro-machined cantilever electrodes extending from the edge of a silicon support. The cantilevers consists of silicon oxide or silicon coated with a metal thin film and provide extremely low contact forces (~ 10^{-5} N) (3). Probes were fabricated with a probe pitch ranging from 1.5 μm to 500 μm (cf. figure 1) and their specifications are summarized in table I.

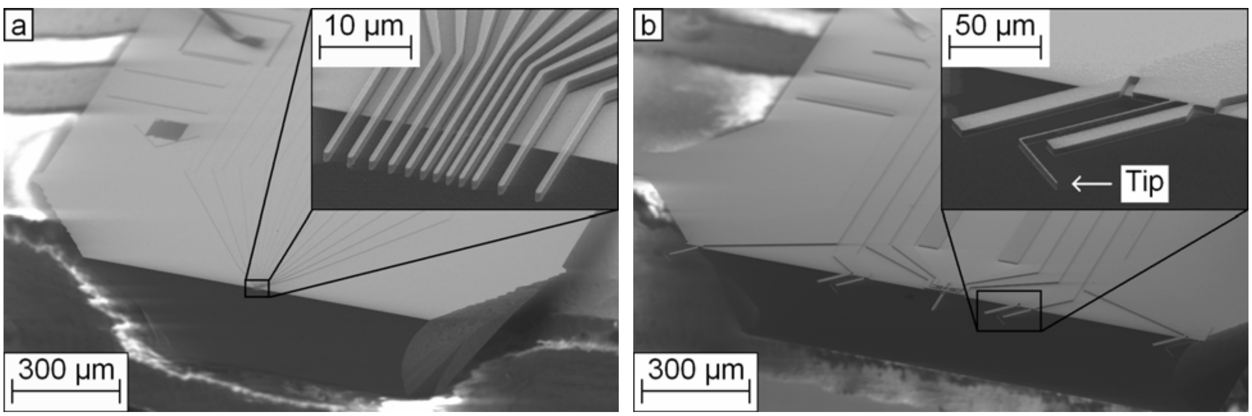

Figure 1: SEM micrographs of (a) a multi-cantilever probe with minimum electrode pitch of 1.5 μm and (b) a 500 μm pitch four-point probe with L-shaped static contact cantilevers.

Probe pitch [μm]	Cantilever material	Electrode material	Probe geometry	Spring constant [N/m]
1.5	SiO_2	Ti/Ni	Straight beam	~ 20
7 – 20	Polysilicon	Ti/Ni or Ti/Au	Straight beam	~ 50
50 – 500	Polysilicon	Ti/Ni or Ti/Au	L-shaped	~ 1-10

Table I: Specifications of four-point probes used in this work.

For the large pitch four-point probes (≥50 μm), the alignment between probe and sample is critical as all four cantilevers should contact the surface at the same time. Any misalignment will necessitate the use of excessive contact force which could possibly result in surface scratching and extreme probe wear. For this reason static contact cantilevers were designed with an L-shaped high aspect ratio geometry to eliminate/minimize surface movements (5). Also, the spring constant of the L-shaped cantilevers was reduced by up to an order of magnitude, such that a deeper engage was possible without probe penetration.

The choice of Ni or Au as electrode material does not impact the measurement precision but can affect probe lifetime/wear and of course acceptability in a CMOS-production in-line environment. All the scans presented in this work have been measured in a random mode (meaning that the sheet resistance data are measured in random order) to rule out the periodic variations in the measurement condition and no deterioration of the sheet resistance precision over the probe life span has been observed. The four-point measurements were performed with the four electrodes being placed on a line orthogonal to the laser annealing scan direction and in a dual configuration mode based on the A and C configuration (cf. figure 7 and equation 2).

UNIFORMITY OF LASER ANNEALING

To study the (local) inhomogeneities following laser annealing, a 30 mm line scan was measured with a 10 µm pitch M4PP and a step size of 25 µm in a direction perpendicular to the laser scan direction. The result is shown in figure 2 and indicates a significant periodic sheet resistance variation.

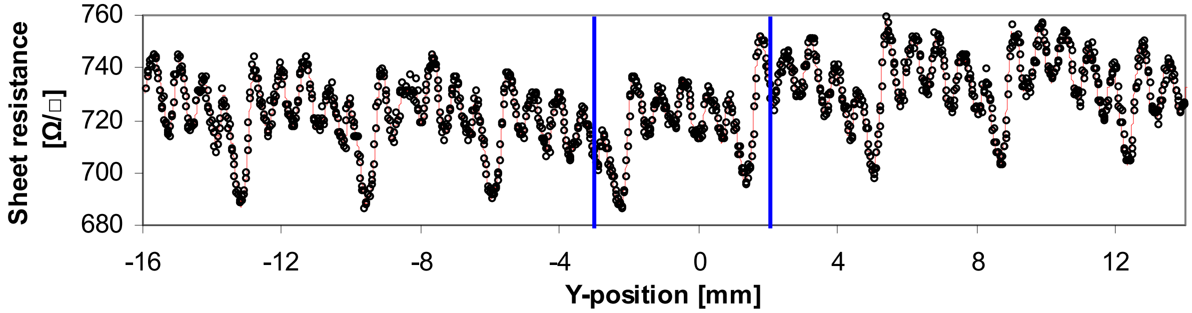

Figure 2: 30 mm sheet resistance line scan perpendicular to the laser scan direction using a 10 µm pitch four-point probe and a step size of 25 µm. The vertical lines define the area which was consecutively probed with different probe pitches (cf. figure 3). A continuous function of the sheet resistance was approximated (thin line) for finite element method (FEM) simulations, cf. figure 9.

In order to study the periodic variations in more detail and the impact of the probe pitch on these results, a 5 mm line scan was measured repeatedly with 11 different probe pitches. All these measurements were performed in the same region as indicated by the vertical lines in figure 2.

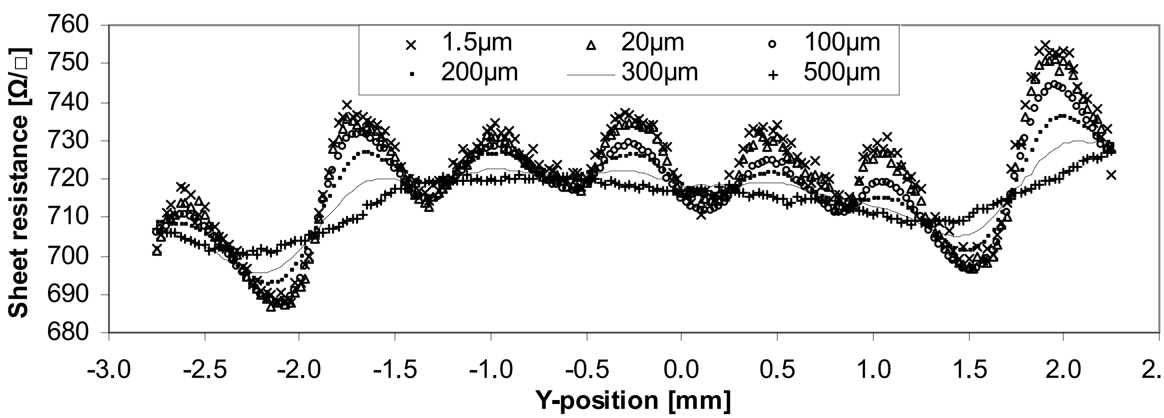

Figure 3: Raw data of a 5 mm line scan with 25 µm step size repeated at the same location with various pitched four-point probes to compare macro and micro sheet resistance. Only selected probe pitch results are shown for easy comparison.

In figure 3 we selectively plot 6 characteristic 5 mm long line scans obtained using different probe pitches. The measurement results demonstrate the probe pitch effect on the measured sheet resistances. The largest probe pitch (500 µm) significantly smoothens out the resistance values and “characterizes” the sheet resistance as being more homogeneous than the smaller pitch probes (≤20 µm).

To quantify the smoothening effect of the large pitched probes the relative standard deviation and peak-to-peak variation of the sheet resistance are calculated and plotted as a function of probe pitch in figure 4. In these plots we restrict the calculations to the oscillations within one period (i.e. 3.65 mm and 750 µm for the two main periods observed in figure 2 – the corresponding line segments are illustrated in figure 5). It is clear that the sheet resistance standard deviation and peak-to-peak variation obtained with the large pitched four-point probes are much less than that obtained using M4PP with 1.5-20 µm pitch for both periods. A small increase in sheet resistance variation is seen with the 500 µm pitch probe relative to the 300-450 µm pitch probes for the 750 µm period (cf. figure 4 right). However, this is likely an artifact caused by other variations such as the 3.65 mm period, i.e. the 500 µm pitch probe is larger than the line scan itself.

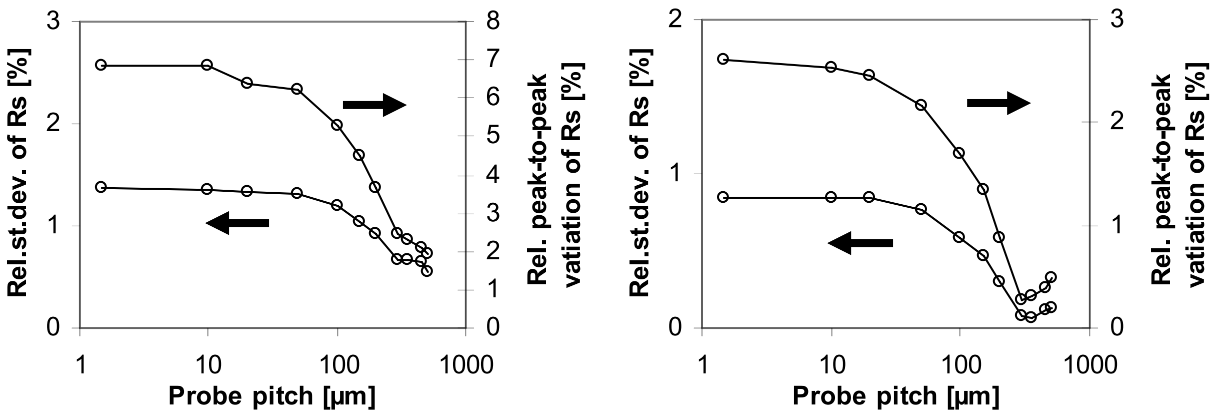

Figure 4: Comparison of the relative standard deviation and relative peak-to-peak variation of the sheet resistance measured with different probe pitches for (left) Y = [-1.825 ; 1.825] mm (cf. figure 5 left) and (right) Y = [0.10 ; 0.85] mm (cf. figure 5 right).

Figure 5 illustrates the two line segments used for the calculations of the sheet resistance variation. The vertical arrows (on figure 5 right) points to unexpected coincident sheet resistance peaks or drops obtained with probe pitch ≤20 µm. The horizontal arrow on the same figure points to a resistance peak obtained with the 1.5 µm pitch probe. This peak is not resolved by the 10 µm and the 20 µm pitch probe, and it remains to be proved if these variations are true or accidental measurement errors.

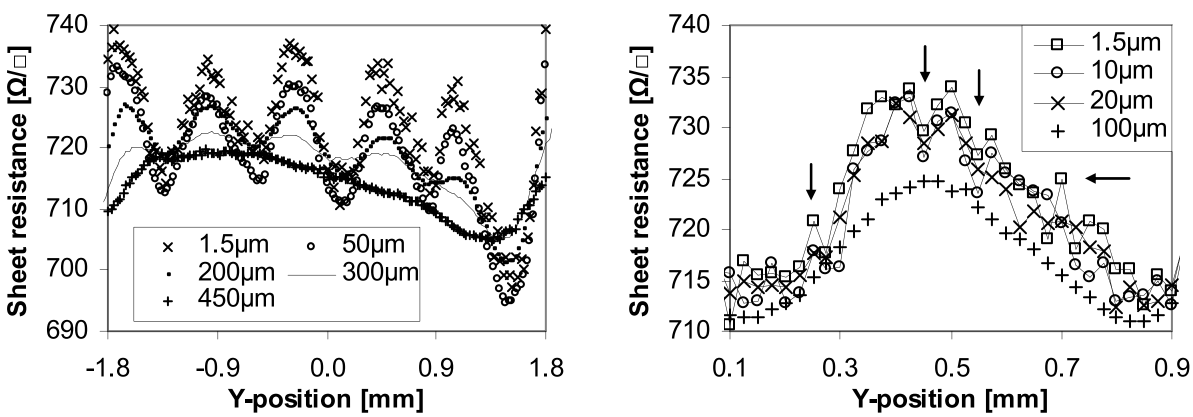

Figure 5: Selected probe pitch and line segment of the 5 mm line scan in figure 3. A line segment was chosen to represent the two main periodic variations of 3.65 mm (left) and ~750 µm (right).

In order to probe non-homogeneities in the laser scan direction, a full 2D-map was made using a 10 µm pitch M4PP and a scan step size of 50 µm and 250 µm in the X- and Y-direction respectively. The result shown in figure 6 indicates not only the periodic pattern in the Y-direction, but also an apparent sheet resistance variation in the X-direction with a period of roughly 500 µm. The peak-to-peak variation in the X-direction is roughly 30 Ω/□ (or 4%). The cause of these variations could be time dependent fluctuations in temperature, laser movement, laser power, etc. and is the subject of further investigation.

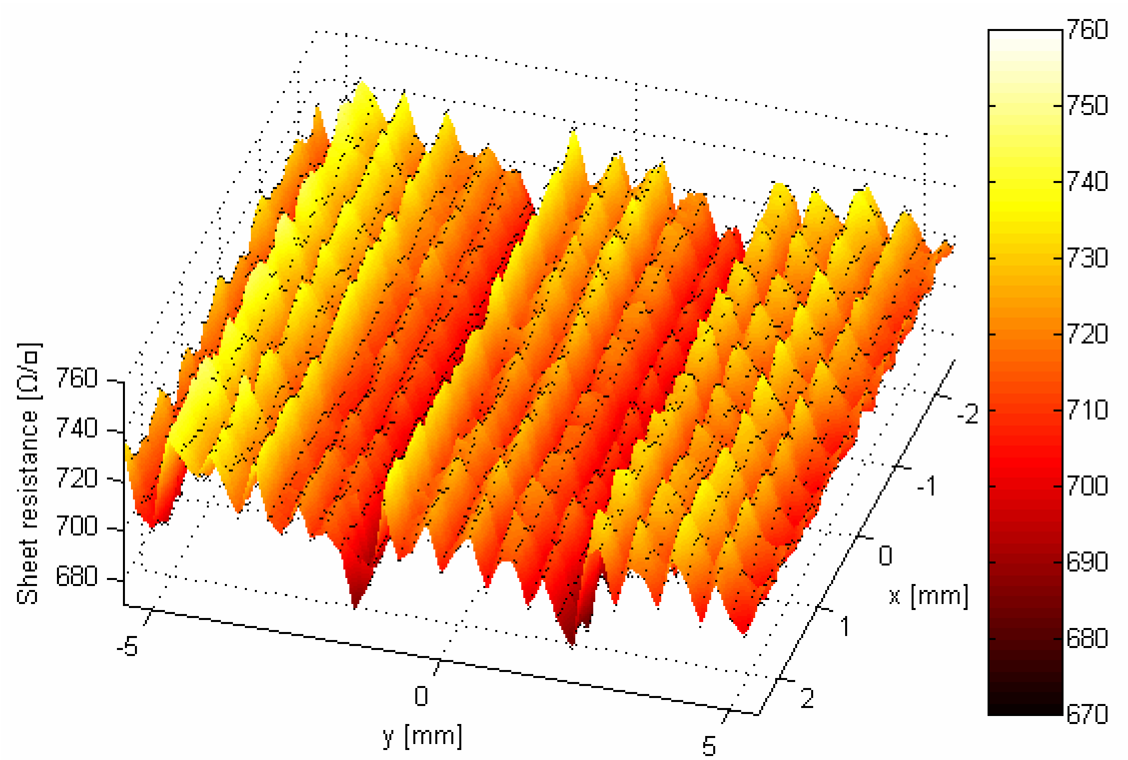

Figure 6: 45×101 point area scan measured with a 10 µm pitch M4PP. The scan step size is 50 µm and 250 µm in the X- and Y-direction respectively. Raw data are represented by dots.

DISCUSSION

Prior to discussing the origin of the probe pitch effect, it is important to address the issue of the probe configuration itself. Basically there exist three independent probe configurations (figure 7) for an in-line four-point probe which can be used to extract the sheet resistance of a conductive infinite sheet.

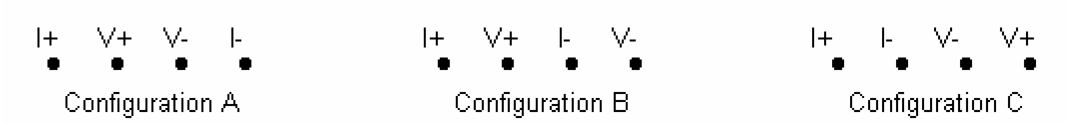

Figure 7: Illustration of three independent four-point configurations. The voltage difference between contact points V+ and V- is measured as a current is passed between contact points I+ and I-.

Generally the sheet resistance is calculated from (6)

$$R_s = \frac{V}{I}C \qquad [1]$$

where I is the applied current, V is the measured voltage and C is a geometrical correction factor that depends on the sample shape and the exact relative contact positions. In the dual configuration mode, the resistance is measured in two of the independent probe configurations, e.g. A and C, and the sheet resistance is calculated based on these two measurements. If the contact points are located along a straight line, positional error along the line is eliminated (7, 8) and off-line positional errors influence the measurement only as a second order effect (8). For the dual configuration mode based on the A and C configuration, the sheet resistance, R_S, is found by solving

$$\exp\left(\frac{-2\pi R_A}{R_S}\right)+\exp\left(\frac{-2\pi R_C}{R_S}\right)=1 \qquad [2]$$

where R_A and R_C are the four-point voltage-to-current ratios measured with the A and C configuration respectively. If the infinite sheet has an otherwise homogeneous sheet resistance, the sensitivity to local resistance variations, $R_{S,L}$, may be calculated using the adjoint system method (9) adapted to the dual configuration mode (8). The normalized four-point probe sensitivity is defined as

$$S=\frac{\partial^2 R_S}{\partial R_{S,L}\partial A}p^2 \qquad [3]$$

where A is the area and p is the probe pitch. To get the change in measured sheet resistance the sensitivity must be integrated over the affected area, e.g. when measuring with a probe pitch of 500 µm if an area of 50×50 µm^2 with a constant sensitivity of 1 changes by 100 Ω/□ then the measured sheet resistance will change by only 1 Ω/□. It follows that a smaller probe pitch must be used in order to correctly characterize such an area.

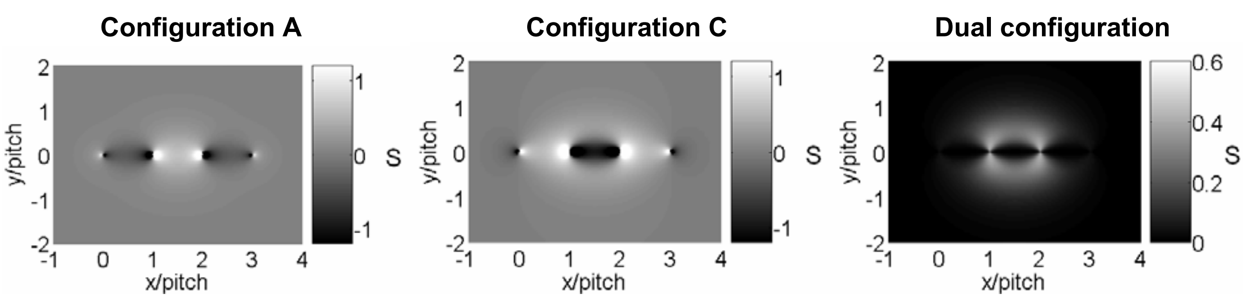

Figure 8: Contour plots of the sensitivity to resistance variations for an in-line four-point probe in the A, C and dual configuration mode. The four contacts are positioned at (x,y) = (0,0), (1,0), (2,0) and (3,0). The sensitivity goes to ±infinity at the contact points for the A and C configuration, however the color scale has been cut off (at S = ± 1.2) to see the surrounding contour. The color scale has not been cut of for the dual configuration contour plot.

In figure 8 the sensitivity, S, as defined by equation 3 is plotted for an equidistant probe pitch. Shown are sensitivities for A, C and dual configuration mode. Configuration B shows a similar sensitivity characteristic as configuration A. For the correct interpretation of the following results, it is important to notice that an in-line four-point probe measuring in the A and C configurations have an opposite sign sensitivity to sheet resistance variations (especially obvious in proximity of the two inner electrodes in figure 8). This means, that if a thin film with otherwise homogeneous sheet resistance has an increased resistance at some point, the sheet resistance measured with a four-point probe centered at this point will be higher for the A configuration and lower for the C configuration.

In order to verify the experimental results of the probe pitch size effect, theoretical simulations using a finite element method (FEM) were performed. In these simulations we used a two dimensional sheet with a spatial variation in sheet resistance based on the 30 mm line scan of figure 2 (the sheet resistance is defined by an approximated continues (wave-) function of Y and with no variation in the X-direction). The FEM simulations were performed with Comsol 3.3 using a 2D model (Conductive Media DC). It was verified that the simulations were insensitive to further mesh refinements and did not suffer from edge effects.

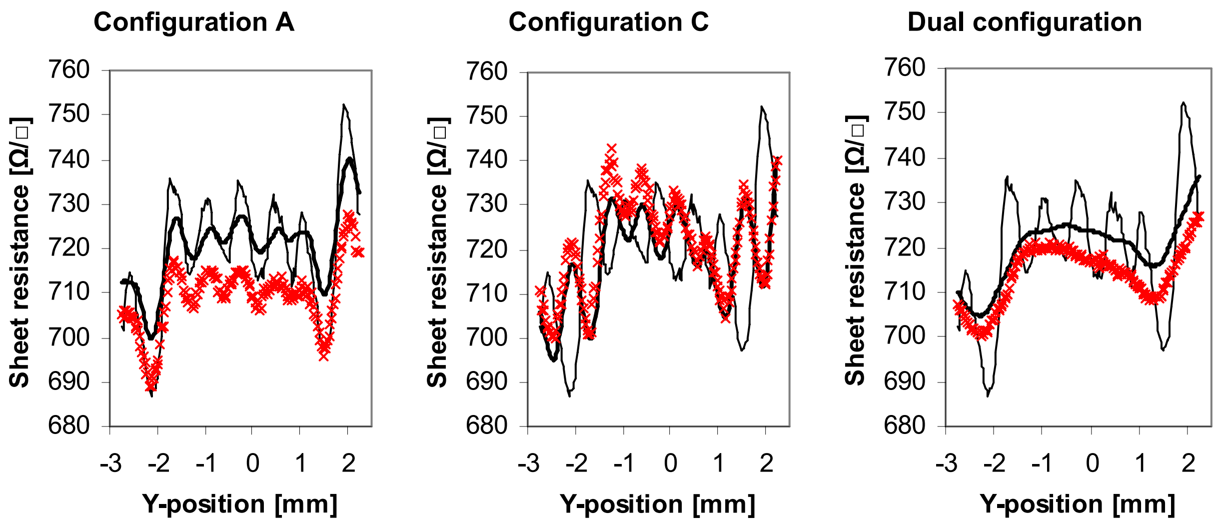

Figure 9: Comparison of configurations A, C and dual for a 500 µm pitch four-point probe on a non-homogeneous USJ. The thin line represents the surface sheet resistance as defined for the FEM simulations (which corresponds to the sheet resistance measured with a 10 µm pitch M4PP). The thick line is the FEM simulated result and the cross represents the experimentally measured result (raw data).

The results are compared in figure 9 to the assumed sheet resistance variation and the experiment data for the corresponding pitch. Whereas the pattern can be clearly reproduced the absolute differ slightly, probably due to the approximations used to describe the sample. It is also interesting to see that the impact of the measurement mode can be clearly reproduced. For instance it appears that the A-configuration gives the most “correct” sheet resistance variation whereas the C-configuration gives a completely out-of-phase sheet resistance pattern, turning peaks to valleys. The apparent good result of the A-configuration mode is due to an interference-like behavior of the positive and negative sensitivity for single configuration measurements. If the sheet resistance was not periodic but rather spike like (only ½ period on an otherwise homogeneous sample), the A configuration would not give a trustworthy representation of the sheet resistance (10). For the same reason the dual-configuration 500 µm pitch probe smoothens the sheet resistance because it only has positive sensitivity. In either case, the conclusion is clear that the 500 µm pitch probe leads to unreliable results and can not be used to assess these small scale variations within the sample.

CONCLUSIONS

Accurate sheet resistance characterization of ultra shallow implants is crucial for further development of CMOS transistors. From this study it is evident that due to their smaller sampling volume, micro four-point probes can resolve sheet resistance variations more precisely than conventional sized four-point probes. This is illustrated in detail by analyzing the (local) non-uniformities of laser annealed junctions. Periodic patterns related to the laser scan overlay pattern and laser beam non-uniformities are observed. These can be characterized in much more detail when using a fine probe pitch whereas the regular 500 µm pitch leads to an excessive smoothening thereby obscuring the finer details of the laser anneal process.

A theoretical analysis of the four-point measurements has been performed assessing the sensitivity of the various configuration modes to small local sheet resistance variations. Whereas in a dual configuration mode the sensitivity is purely positive, a single configuration four-point measurement may exhibit both positive and negative sensitivity to resistance variations leading to an unexpected correlation to local inhomogeneities. Based on this formalism also the effect of probe pitch on the measurements has been simulated. These simulations confirm the experimental observations that the 500 μm pitch four-point probe significantly underestimates the sheet resistance variations present on a laser annealed ultra shallow junction (20 nm).

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