Micro Four-Point Probe with High Spatial Resolution for Ion Implantation and Ultra Shallow Junction Characterization

Daniel Kjaer[1], Rong Lin[1], Dirch Hjorth Petersen[1, 2], Petros M. Kopalidis[3*], Ronald Eddy[4], David A. Walker[4], William F. Egelhoff, Jr.[5], Larry Pickert[6]

[1]CAPRES A/S, Scion-DTU, Building 373, DK-2800 Kgs., Lyngby, Denmark
[2]DTU Nanotech - Dept. of Micro and Nanotechnology, Technical University of Denmark, B-345 East DK-2800 Kgs. Lyngby, Denmark
[3]Technological Educational Institute of Thessaloniki, Sindos 57400, Greece
[4]Innovion Corporation, Chandler, AZ 85226, USA
[5]National Institute of Standards & Technology, Gaithersburg, MD 20899, USA
[6]Microchip Technology Inc., Chandler, AZ 85224, USA

* kopalidis@urgrad.rochester.edu

Abstract. The application of micro four-point probe technique in ion implantation non-uniformity mapping and analysis is demonstrated in this work. The technique uses micron-size probes with electrode pitch of 10 µm to achieve greatly enhanced spatial resolution of sheet resistance (Rs) measurements. Rs non-uniformities due to uneven dopant distribution or activation can be mapped with improved accuracy, making it easier to detect implanter scanning problems, dose and charge control malfunctions and annealer related non-uniformities. The technique's superior performance in spatial resolution over conventional four-point probe measurements is demonstrated by zero edge exclusion sheet resistance measurements at the wafer edge. In addition, the technique is used to investigate potential Rs variations between equivalent As+ and As_2+ implants with the same effective energy. Finally, repeatability and reproducibility are investigated by making multiple measurements on a selected ULE implanted and annealed wafer.

Keywords: Sheet resistance, four-point probe, ion implantation, process control, diagnostics
PACS: 07.10.Cm; 84.37.+q; 85.85.+j

INTRODUCTION

A major concern in ion implantation process qualification and control is to ensure consistent uniformity of dopant distribution over large numbers of processed wafers. Modern ion implanter design involves complex mechanisms of ion beam and/or wafer scanning as well as dose and charge control that, when deviating even slightly from their normal operation can result in unacceptable non-uniformities and seriously affect implanter uptime and availability. Sheet resistance (Rs) measurements by conventional four-point probe (FPP) have long been used as a principal way of detecting and analyzing such wafer non-uniformities [1], however recent work has demonstrated that the technique sometimes becomes limited in its usefulness to characterize ultra shallow implants, due to probe penetration [2] and leakage current [3], as well as non-uniformities, due to limited spatial resolution [4]. The micro four–point probe (M4PP) technique, utilizing micron sized and non-destructive probes, provides a straightforward solution to these difficulties.

In this work the main focus for Innovion is to determine the usefulness of the M4PP system, manufactured at Capres for process monitoring, process diagnostics and for wafer detail correlation to die problems.

EXPERIMENTAL

n- and p-type 200 mm wafers were implanted in a batch, high current ion implanter (Axcelis GSD-200E2) with energies and doses as shown in Table 1. The wafers were annealed in a rapid thermal annealer at either of two locations – Innovion and Microchip – using an Axcelis-Reliance 850 and a Mattson-AST SHS2800 respectively. The anneal recipe used with the Axcelis Reliance 850 rapid thermal annealer is 35 sec, 1100^{o}C with 50% N_2 in air. A different anneal recipe is used with the Mattson-AST SHS2800, as follows: 18 sec, 1050^{o}C with 10% O_2 in N_2 gas.

Test #	Species	Energy, keV	Dose, ions/cm^2	Rs, Ohm/sq. Capres (M4PP)	Rs, Ohm/sq. CDE (B-type FPP)	M4PP-FPP Diff., %	Notes
1	As+	2	1E15	163.64	146.87	10.80	Flood on
2	As+	2	1E15	149.25	141.82	5.11	Flood off for comparison
3	As_2+	2	1E15	152.85	148.94	2.59	Dimer; Particle energy and dose are same as in Run 1
4	B+	2	1E15	155.78	153.17	1.69	
5	BF_2+	3	1E15	273.52	268.94	1.69	Effective B energy = 0.67 KeV
6	As+	2	1.2E15	132.08	126.25	4.51	Dose Sensitivity vs. Test #1
7	As+	2	8E14	203.57	191.32	6.20	Dose Sensitivity vs. Test #1

TABLE 1. Experimental matrix of implanted species, energies and doses.

The FPP used at Innovion is a CDE ResMap Model 178 with a 1 mm pitch probe. The M4PP consists of an array of micro-machined, metal coated silicon cantilevers providing an extremely low contact force (~ 10^{-5} N) [4]. In this work M4PPs with 10 µm probe pitch were utilized.

RESULTS AND DISCUSSION

The average sheet resistances (Rs) measured with the CDE and the M4PP (see Table 1) indicate generally quite good agreement between the two instruments for all implanted wafers, with the differences in average Rs within 6.2 % with the exception of the first implant for which the difference is 10.8 %. It is not clear at the time of publication what caused the large difference in this implant. For all implants, the Capres M4PP gives slightly higher Rs values than the CDE. This is partially due to a difference in lab temperature, 19.5 °C for the CDE and 26.5 °C for the M4PP, and most likely partially due to leakage current on the CDE part [2,3]. The higher roughness of the CDE contour maps origins from unintended rotations of the sample during measurements as the wafer is not fixed in the tool.

Rs Comparison for Flood Off, Dimer and BF_2 Implants

The first three implants, cf. Table 1, involve a comparison of sheet resistance between FPP and M4PP for a baseline 2 keV, 1e15 As^+ implant, the same implant with the charge neutralization device of the implanter turned off and an equivalent As dimer implant. The Rs values for the baseline implant are 146.87 and 163.64 Ω/sq respectively for the 4PP and M4PP, a 10.80 % difference. Both probes show a drop in Rs and worsening uniformity when the charge neutralization is turned off, an expected consequence of the ion beam blowing up as it traverses the Si wafer from the aluminum disk. The Rs maps for the flood-off implants are shown in Figure 1.

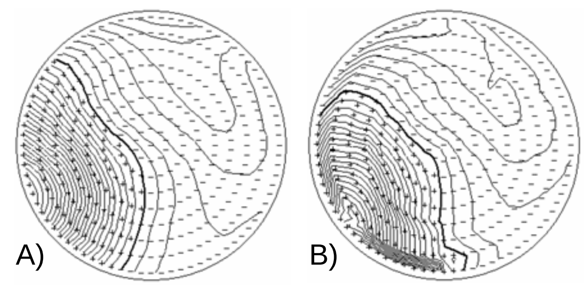

FIGURE 1. Rs contour maps from a) the M4PP and b) the CDE for a flood-off implanted wafer (notch down, 2 % contour intervals).

Compared to the baseline the Rs values from the As_2^+ implanted wafer differ by -1.4 % and 6.6 % for the FPP and the M4PP probes respectively. These variations are up to 3 times higher than previously published results [5], which could be due to the different type of implanter used in this study.

The next comparison involves a 3 keV, 1e15 BF_2 implant (annealed in the SHS2800) with an effective B energy of 0.67 keV. The Rs maps from the BF_2 implant are shown in Figure 2.

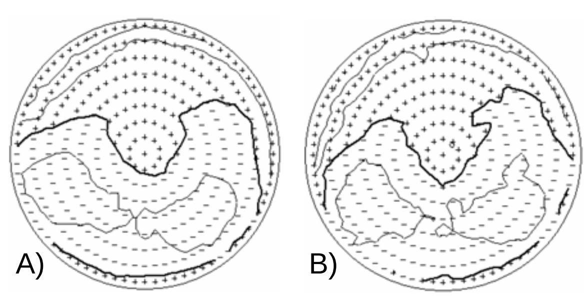

FIGURE 2. Rs contour maps from a) the M4PP and b) the CDE for a 3 keV, 1e15 BF_2 implanted wafer (notch down, 1 % contour intervals).

Reproducibility, Repeatability and Dose Sensitivity

Repeatability and reproducibility studies of the M4PP were performed on the BF_2 implant. The repeatability of the instrument was tested at five points on a 2×2 mm square. The sheet resistance at each position was measured repeatedly 20 times in a random manner. The mean Rs, the standard deviation (SD), and the relative SD calculated for the five points are given in Table 2.

X / µm	Y / µm	<Rs> / Ω/sq	SD / Ω/sq	SD / %
-1000	-1000	275.2	0.25	0.09%
-1000	1000	275.41	0.39	0.14%
0	0	275.24	0.24	0.09%
1000	-1000	275.15	0.25	0.09%
1000	1000	275.42	0.16	0.06%

TABLE 2. Repeability data for 5 locations measured 20 times each in a random manner.

The reproducibility of the M4PP was checked for four different probes: one used probe with more than 1000 touches and three new probes. A 2.5 mm line scan with 100 µm step size was repeatedly measured by these probes at the same locations. Table 3 summarizes the measurement results.

	Probe 1 (old)	Probe 2 (new)	Probe 3 (new)	Probe 4 (new)
<Rs> / Ω/sq	274.64	274.52	274.66	274.55
SD / Ω/sq	0.23	0.24	0.18	0.20
SD / %	0.08	0.09	0.06	0.07

TABLE 3. Reproducibility on a 2.5 mm line scan repeatedly measured by four M4PPs.

An additional long term reproducibility test was performed in a scan area of 5x5 points each separated by 10 mm. The scan was measured 3 times a day (with a time span of 4 hours) for 5 days over a period of 7 days and the wafer was transferred to and from the measurement system during the test. In Figure 3 the mean Rs values as well as the temperature for each measurement time are plotted.

The relative SD of the 15 scans was calculated to be 0.08 %. It is evident that the measurement deviations are correlated to and can be explained by the variation in lab temperature.

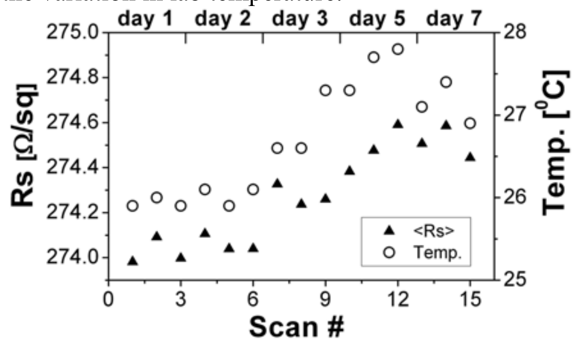

FIGURE 3. Rs and temperature for long term test.

The 2 keV, 1e15 As^+ implant (test # 1) was analyzed for dose sensitivity by running two additional implants with +/-20% dose difference (tests # 6 and 7). The dose sensitivity as described in reference [6] was 1.1 and 1.0 for the M4PP and the conventional 4PP respectively. This is in good agreement with the theoretical dose sensitivity which is 1.04 for the choice of doses while assuming constant mobility and 100% dose activation.

Edge Measurements

The Capres M4PP has due to the microscopic tip separation virtually no edge exclusion. This has been shown by performing a line scan all the way to the wafer edge and beyond (see Figure 4). The step size of the line scan was lowered to 5 µm as the probe approached the edge. For each measurement point an Rs value was read out together with the z-position of the probe thus effectively mapping the topology of the wafer edge. These results are plotted in Figure 5 and 6 together with information of the wafer slope, α and the measured sheet conductance, Gs. Beyond the wafer edge a significant increase in Rs is observed mainly due to the smaller projected area of this region with respect to the direction of the ion beam. The estimated sheet conductance based on the expression: $Gs \propto dose \times \cos(\arctan(\alpha))$, was found to deviate less than 2 % from the measured values for a slope angle up to 20° and the result was reproducible on different wafers.

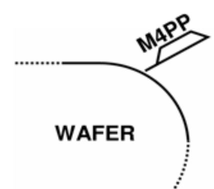

FIGURE 4. M4PP measuring beyond the wafer edge.

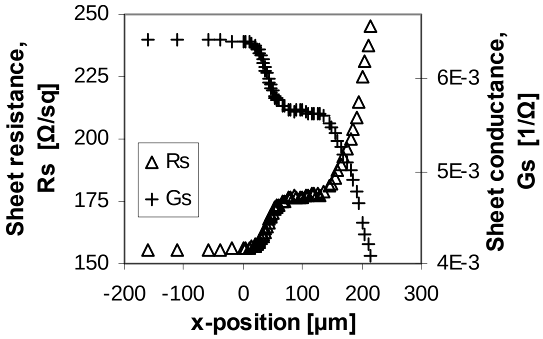

FIGURE 5. Rs and Gs as a function of x-pos.

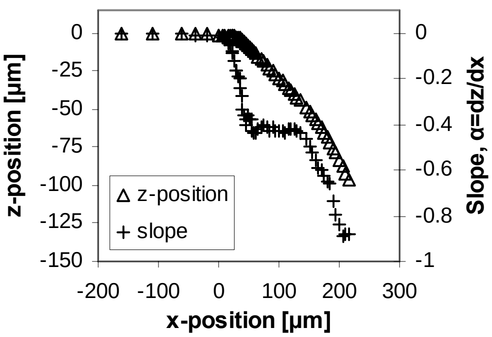

FIGURE 6. z-pos. and slope as a function of x-pos.

The M4PP can perform similar high resolution line/area scans anywhere on a wafer and thus the tool allows the user to map even very confined areas such as test pads in scribe lines, which can not be measured using a conventional FPP. With its micron-size probes and nanoscale positioning the M4PP is a natural choice for the assessment of the "critical diameter" that coincides with the corrected scan plane of all implanter types. This can be used to assess new recipe setups as well as to verify possible drift in that setup after longer wafer runs.

CONCLUSIONS

In this work we investigate the advantages of using M4PP technique for dose and uniformity control in comparison with the conventional FPP. In general we find that conventional FPP measures lower Rs values than M4PP which has previously been reported to be related to probe and substrate leakage current present for conventional FPP measurements. The M4PP technique utilizes micron-size probes and spacing between them, thus allowing for very localized measurements. This can give high resolution Rs information in tight areas of the wafer and can help to identify and trouble-shoot process problems related to implant and/or anneal. The zero probe penetration and micron-size probe pitch ensure more accurate and reliable measurements and overcome the shortcomings of a conventional FPP. Furthermore we demonstrate the repeatability and reproducibility of the Capres M4PP system to be below 0.1 %.

The identification of commercial instruments is to specify the experimental conditions and does not imply any NIST endorsement or recommendation that it is necessarily the best instrument for the purpose.

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