Microprobe Metrology for direct Sheet Resistance and Mobility characterization

Peter Folmer Nielsen[1] Dirch H. Petersen[2], Rong Lin[1], Ane Jensen[1], Henrik H. Henrichsen[1, 2], Lauge Gammelgaard[1], Daniel Kjær[1, 2], Ole Hansen[2, 3]

Tel: +45 2363 8313; Fax: + 8882 1499; email: pfn@capres.com

[1)] CAPRES A/S, Scion-DTU, building 373, DK-2800 Kgs. Lyngby, Denmark

[2)] DTU Nanotech, Technical University of Denmark, building 345B, 2800 Kgs. Lyngby, Denmark

[3)] CINF, Technical University of Denmark, building 345B, 2800 Kgs. Lyngby, Denmark

Introduction

Collinear microprobes are presently entering semiconductor fabs worldwide for routine sheet resistance measurements directly on blanket- and patterned wafers. The use of a collinear microprobe in combination with low noise measurement electronics, high resolution positioning stages and pattern recognition enables extraction of the very local sheet resistance variation on micron sized structures and ultra thin conducting layers. In addition to direct sheet resistance characterization of Ultra Shallow Junctions (USJs), Magnetic Tunneling Junctions (MTJs), SiGe, Silicides, Nitrides and Ultra Thin Metal layers, the new generation of probing tools is equipped with a Hall effect measurement capability enabling direct extraction of carrier mobility and sheet carrier density.

Here we present the advances of the micro four-point probe (M4PP) metrology and focus on what is required to do direct and reliable measurements of sheet resistance, mobility and active carrier density on both blanket- and patterned wafers.

The Collinear Micro Probe

Since the development of the M4PP by C. L. Petersen et al. in 1999 [1] it has mainly been used for direct characterization of magnetic tunnel junctions (MTJs) via the current-in-plane tunneling (CIPT) method, [9] and is now an important metrology tool for the development of MTJ devices such as hard disk read heads and magnetic random access memory (MRAM). The first generation of cantilever based M4PP consists of four to twelve straight collinear cantilevers, see fig. 1.

A fundamental problem in micro four-point measurements is the electrical- and mechanical contact between the electrode tips and the surface to be measured. The M4PP-pin typically consists of a non-conducting cantilever with a 100-150 nm metal layer deposited to enable the electrical contact to the surface to be measured. During measuring of sheet resistance the metal layer is in physical- and electrical contact with the surface to be measured and is sensitive to sub-micrometer sized movements [10]. Thus a M4PP with straight cantilevers (fig. 1) has a limited lifetime due to mechanical wear. Typically the lifetime of this type of probes is limited to few hundred measurements.

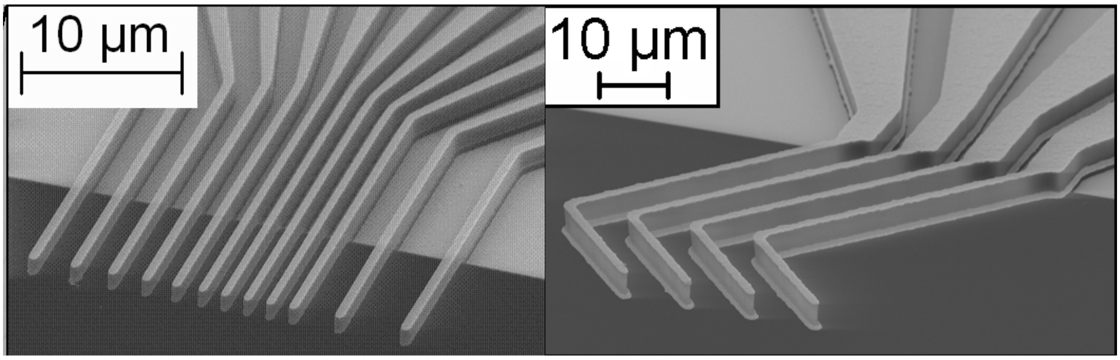

Figure 1: micro 12 point probe (left), L-shaped 4 point probe (right).

In 2008 Dirch H. Petersen et al. [10] presented a new M4PP design that extends the lifetime of a M4PP from a few hundred measurements to several thousand measurements per probe. This new design has a three-way flexible cantilever which obtains a static surface contact to the surface of interest, during measurement, see fig. 1(right).

M4PP measurement

In a M4PP measurement a current I_0, is passed through a conductive sample between two current injection electrodes while the voltage potential difference, V, is measured between the two remaining electrodes. The four-point resistance, $R_i = V/I_0$, can be calculated from six non-trivial combinations of current and voltage electrodes, fig. 2. (A, A'; B, B' and C, C' configurations). In R_i the subscript i denotes the four-point configuration.

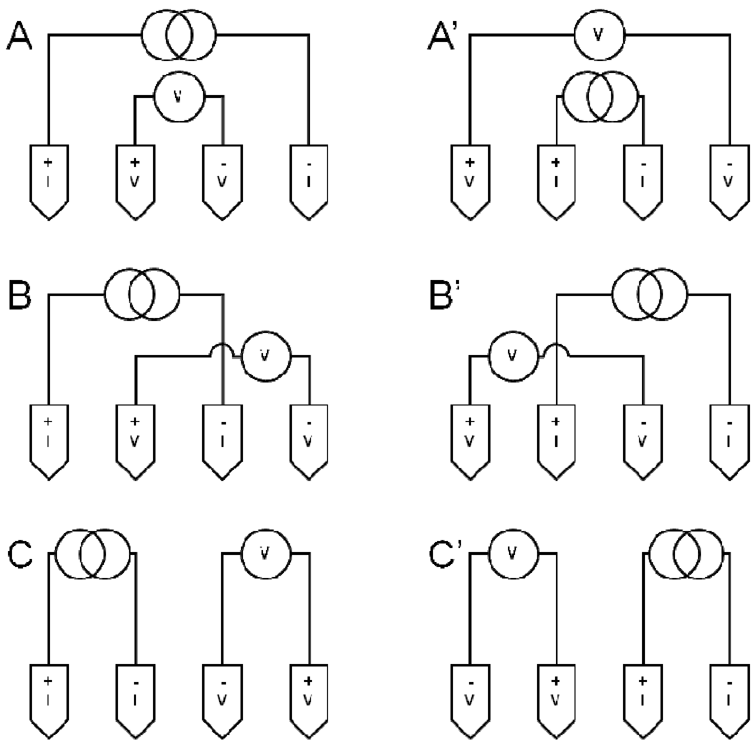

Figure 2: The six non-trivial electrode configurations, A, A', B, B', C and C'.

In sheet resistance measurements, the average resistances of two configurations are used to eliminate the inline position errors of the M4PP, by using the van der Pauw equation [8]:

$$\exp(2\pi R_{AA'}/R_P) - \exp(2\pi R_{BB'}/R_P) = 1$$

where $R_{AA'}$ and $R_{BB'}$ are the average resistances of R_A and $R_{A'}$ or R_B and $R_{B'}$ respectively. R_P is the pseudo sheet resistance, which far from any boundary is the sheet resistance, R_S. Any two combinations of configuration types can be used for the position correction, i.e. $R_{AA'}$ and $R_{CC'}$ or $R_{BB'}$ and $R_{CC'}$ are also valid.

Small pads

M4PP measurements on samples with dimensions of the same scale as the probe pitch (typical 8 μm) are strongly affected by the proximity of the sample boundaries.

In 2009 Sune Thorsteinsson et. al [3] showed that using dual configuration measurements, the sheet resistance can be extracted when the M4PP are positioned in proximity of a mirror plane on small structure/pads with dimensions of only a few times the probe pitch.

The combination of the M4PP and a high precision positioning stage enables the probe to be positioned in the "sweet spot", cf. fig. 3, in which it is possible to do correction free extraction of sheet resistance with sufficient accuracy.

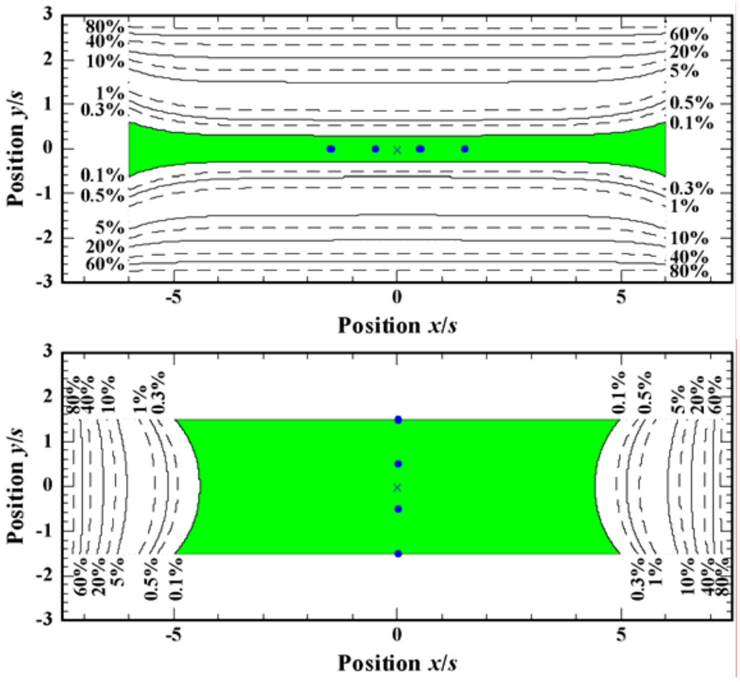

Figure 3 (adapted from [3]): The "sweet spot" (green area), where correction-free dual configuration RS may be measured with an error <0.1 %. The frame of each figure indicates the boundaries of the rectangles (15s×6s and 6s×15s), and the probe location is defined by the center of the four electrodes with a pitch of s. The relative area of the "sweet spot" is largest when the four electrodes are placed parallel to the short side of a rectangle (bottom right).

Micro-Scale Hall effect measurements

Accurate characterization of Ultra Shallow Junctions (USJ) is important in order to understand the principles of junction formation and to develop implant and annealing technologies. A M4PP measurement can reveal the very local sheet resistance variation of the ultra thin junction layer without probe pin penetration through the layer of interest. In measurements of laser annealed wafers, the local sheet resistance can be measured and the result can be used for fast process optimization feedback.

Sheet resistance measurements can reveal the variation of resistance on blanket or patterned wafers, but cannot give direct feedback of the mobility and active carrier density, since these are all related through:

$$R_S = 1/e\ \mu_H\ N_{HS}$$

In 2009, D. H. Petersen et al. [5] concluded that it is possible to perform high precision micro-scale Hall effect measurements using a collinear M4PP, by placing it close to an insulating barrier e.g. a cleaved edge or on a small structure/pad. A strong magnetic field perpendicular to the measurement plane is used to induce a Hall signal, which is measureable by the collinear probe close to the barrier. A Hall sheet resistance, R_H, can be determined from the resistance difference R_B-$R_{B'}$. The average Hall mobility can be determined using the relation [5]:

$$\langle\mu_H\rangle = R_H / R_S Z B$$

Where Z is +1 or -1 for p-type or n-type semiconductors respectively and B is the magnetic field strength.

Capres microRSP

In the Capres probing tools it is possible to apply an alternating measurement current, I_0, in the range of 10nA to 2.5mA. Lock-in measurements can be set up to automatically extract R_A, $R_{A'}$; R_B, $R_{B'}$ and R_C, $R_{C'}$ from the six non-trivial combinations of current and voltage electrodes.

At present the three-way-flexible M4PP is used in the Capres microRSP-A300 fully automatic probing tool for in-line sheet resistance measurement on blanket- and patterned wafers, see fig. 4. In this tool, a build in probe cassette system consisting of 4 cassettes with 25 M4PP each enables the tool to perform up to 100.000 sheet resistance measurements before it has to be reloaded.

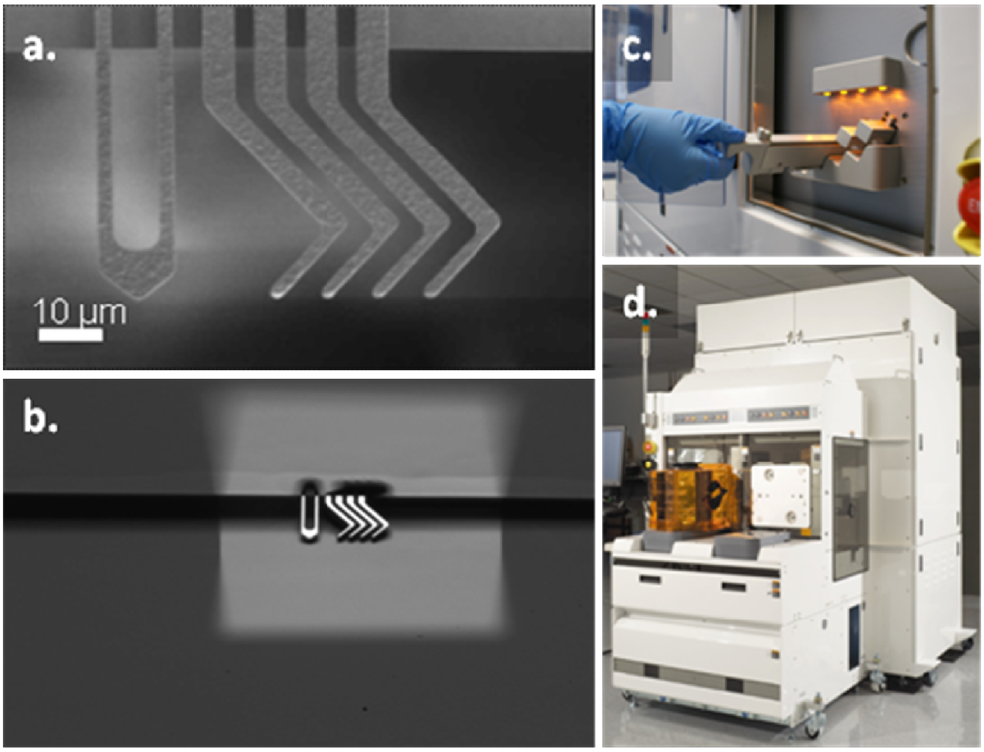

Figure 4: Three-way flexible 8 µm pitch Four Point Probe with Strain Gauge cantilever (a). Microprobe approaching test pad on patterned wafer (b).Fully automatic microRSP-A300 platform with probe magazine load (c) and wafer cassette loading (d).

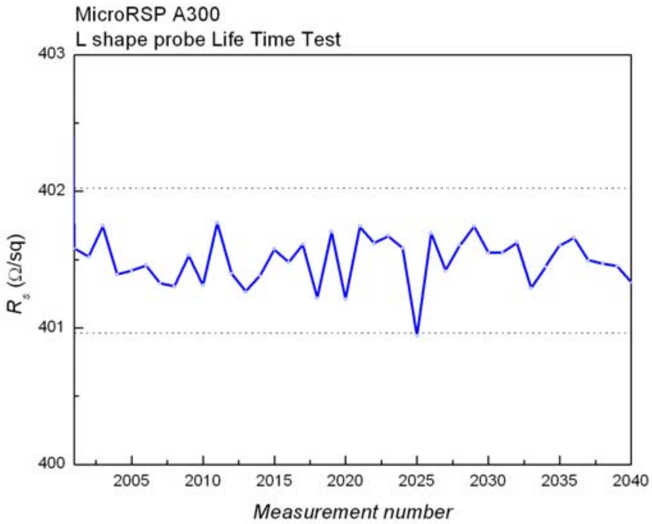

Figure 5: 40 measurements with an L-shaped probe (fig. 3a) made in an area with constant RS, after 2000 initial measurements. The standard deviation is 0.04%, the dashed lines are average RS +/- 3σ.

Figure 5 shows the result of a lifetime test on standard Capres microRSP-A300 L-probes. M4PPs based on the tree-way flexible design principle is at present also used for direct mobility and active carrier density measurements using the Capres microHall-M300 semiautomatic probing tool. In this tool the Micro probe has to be interchanged after approximately 1000 measurements depending on sample type.

A direct- and accurate measurement of sheet resistance, carrier mobility and sheet carrier density on blanket and patterned wafers requires that the M4PP is combined with a stable mechanical tool platform that reduces mechanical- and acoustic vibrations from the surrounding environment to a minimum. To be able to position the M4PP with a resolution of a few microns (+/- 2 µm) on blanket and patterned wafers both a high resolution X-Y positioning stage and a high resolution pattern recognition system is part of the tool platform.

At present, using a M4PP with a probe pin pitch of 8 µm, it is possible to perform accurate sheet resistance measurements on structures/pads down to 50 x 50 μm^2 square [3] and mobility and active carrier density measurements on structures down to 70 x 70 μm^2 square [9].

Summary

The M4PP measurement technique has gained increased interest from the semiconductor industry for direct sheet resistance measurements on ultra thin layers and small structures/pads. Several fully automatic microRSP probing tools are today in use for in-line sheet resistance measurements on blanket and patterned wafers. Using the next generation of microRSP probing tools it will be possible to perform both sheet resistance, mobility and active carrier density measurements using the collinear M4PP. In this article we demonstrate the various techniques necessary to perform high quality measurements using the M4PP and present the technical progress made during the last few years.

References

1. C.L. Petersen, R. Lin, D.H. Petersen, P.F. Nielsen, Proceedings of the 14th IEEE International Conference on Advanced Thermal Processing of Semiconductors, RTP 2006 (IEEE, New York, 2006) p.153.
2. D.H. Petersen, R. Lin, T.M. Hansen, E. Rosseel, W. Vandervorst, C. Markvardsen, D. Kjær, P.F. Nielsen, J. Vac. Sci. Technol. B 26, p. 362 (2008).
3. S. Thorsteinsson, F. Wang, D.H. Petersen, T.M. Hansen, D. Kjær, R. Lin, J.-Y. Kim, P.F. Nielsen, and O. Hansen, Rev. Sci. Instrum. 80, 10pp (2009).
4. D.H. Petersen, O. Hansen, T.M. Hansen, P. Bøggild, R. Lin, D. Kjær, P.F. Nielsen, T. Clarysse, W. Vandervorst, E. Rosseel, N.S. Bennett, N.E.B. Cowern, J. Vac. Sci. Technol. B 28, C1C27-C1C33 (2010).
5. D.H. Petersen, O. Hansen, R. Lin, P.F. Nielsen, J. Appl. Phys. 104, 013710 (2008).
6. D.H. Petersen, O. Hansen, R. Lin, P.F. Nielsen, T. Clarysse, J. Goossens, E. Rosseel, and W. Vandervorst, Proceedings of the 16th IEEE International Conference on Advanced Thermal Processing of Semiconductors, RTP 2008 (IEEE, New York, 2008) p. 251.
7. Østerberg et al. J. Appl. Phys. 110, 033707 (2011)
8. L. van der Pauw, Philips Research Reports, vol. 13, pp. 1–9, 1958.
9. D. C. Worledge and P. L. Trouilloud, Appl. Phys. Lett. 83, 84, 2003
10. D. H. Petersen, O. Hansen, T. M. Hansen, P. R. E. Petersen, and P. Bøggild, Microelectron. Eng. 85, 1092, 2008.