Microprobe Metrology for direct Sheet Resistance and Mobility characterization

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Co-Founder

Capres A/S

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DTU

DTU Nanotech
Department of Micro- and Nanotechnology

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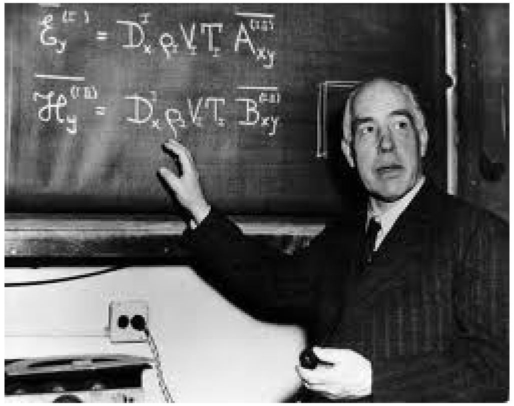
Denmark…..The land of….

Hans Christian Andersen

Danish Pastry

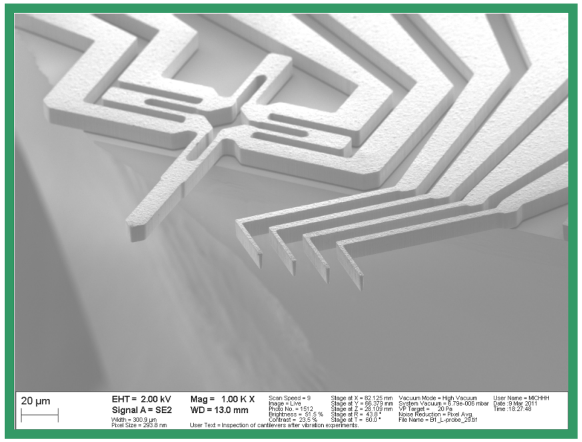


Niels Bohr

Danish Bacon

AND

Microscopic Multi Cantilever Probes



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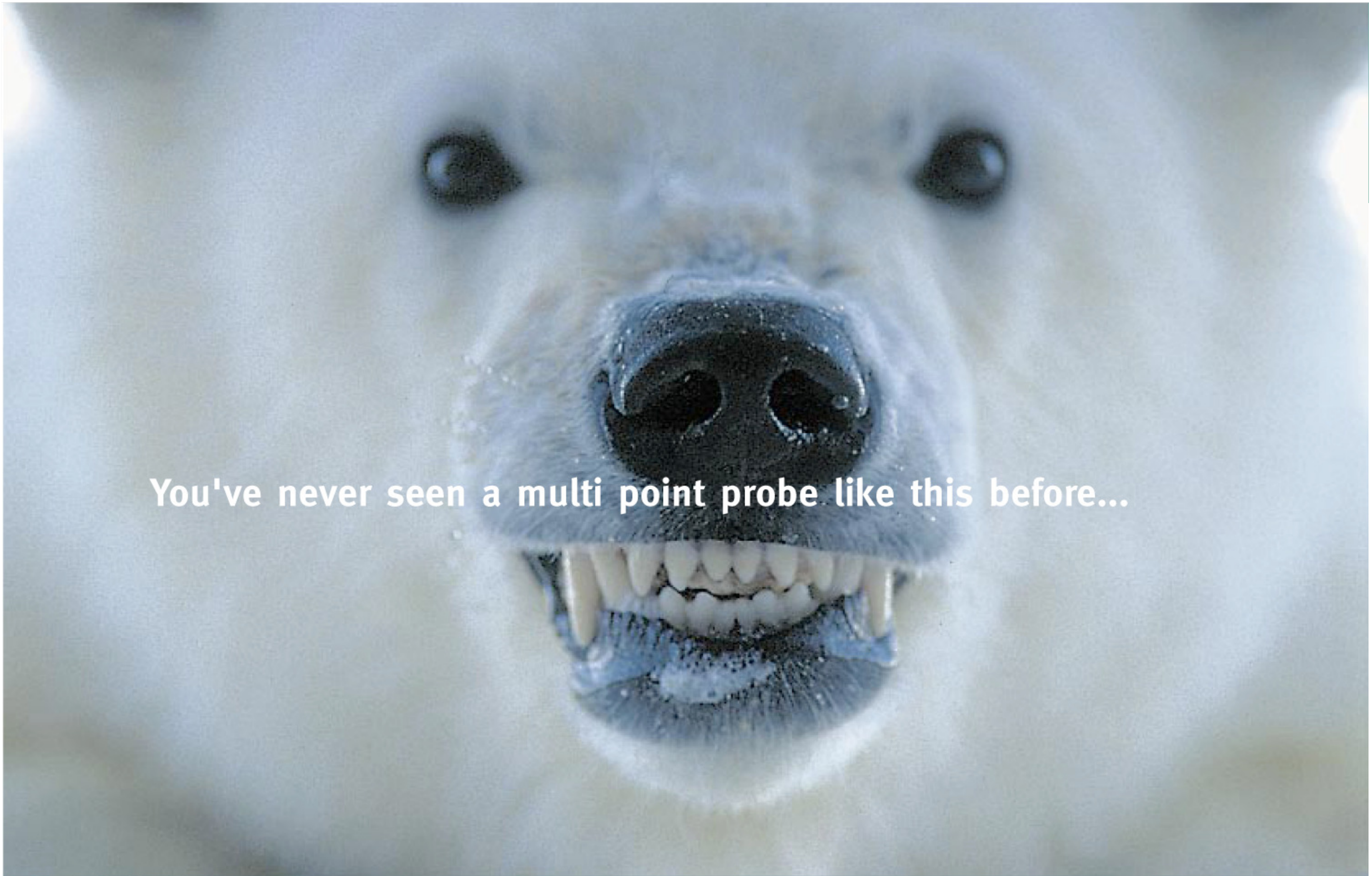

Photo by Peter F Nielsen @ Northeast Greenland

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COPENHAGEN APPLIED RESEARCH

Outline

- History
- Sheet resistance (Micro Four Point Probe , M4PP)
  - Microprobes and Basic Tool requirements
  - Dual configuration, Small samples, Fundamental limitations
  - Application
- Micro Hall effect
  - Basic Hall-Effect Measurement and Hall-effect measurement using a Collinear M4PP
  - Applications
- Capres Fact-Sheet, Conclusion and Discussion

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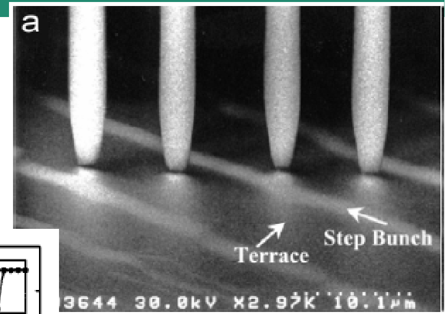
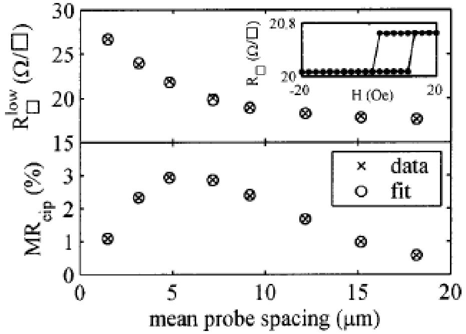
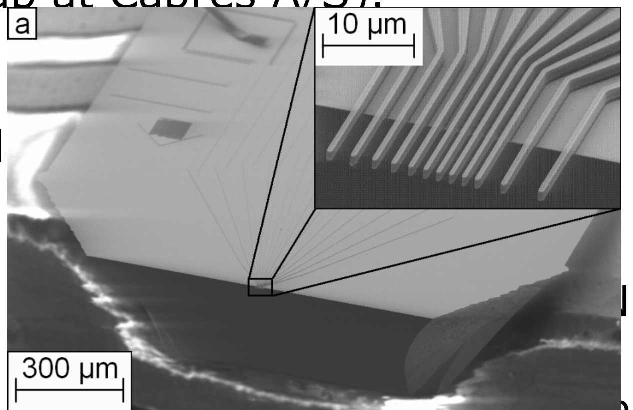
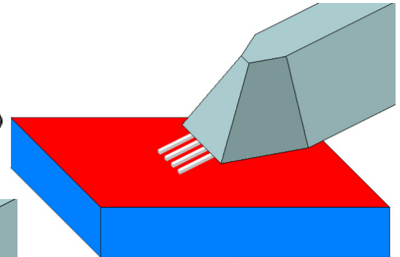
History

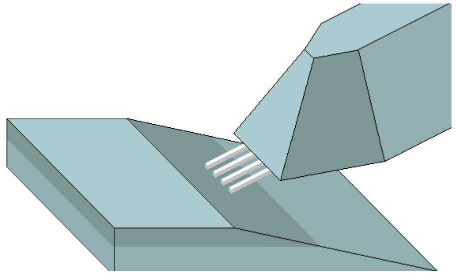


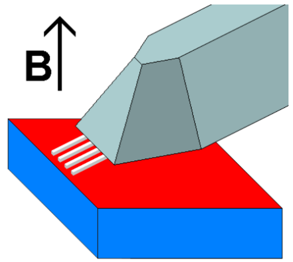
- 1999-2000 First M4PP developed and Capres A/S Founded
- 2003 – Magnetic tunnel junction characterization. (D.C.Worledge, et al.)
- 2005 – USJ R_S characterization (Group at Capres A/S).
- 2006 (T. Cl
- 2008 (D.H. lielsen).
- 2012 – Direct Leakage Current measurement (Rong Lin et. al at IIT 2012).



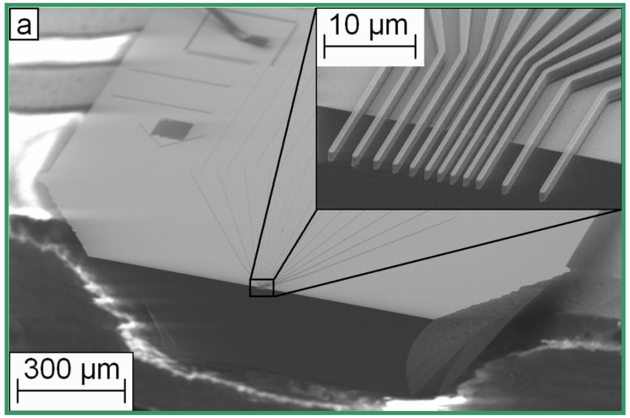


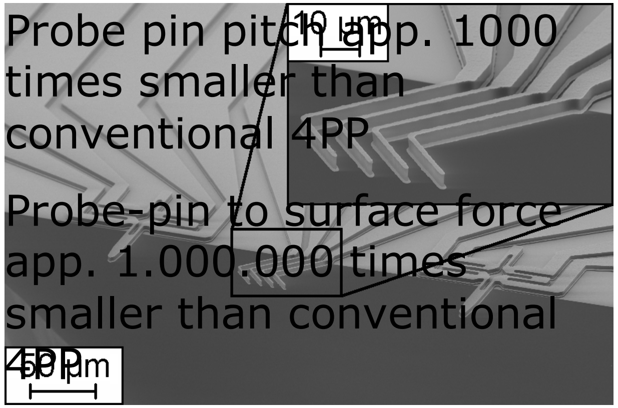






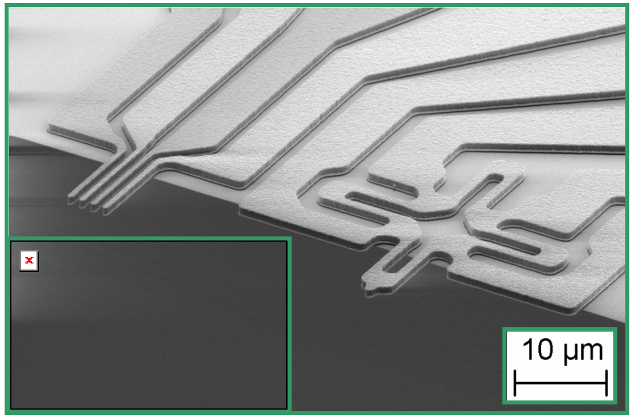
Microscopic Multicantilever Probes M4PP & M12PP

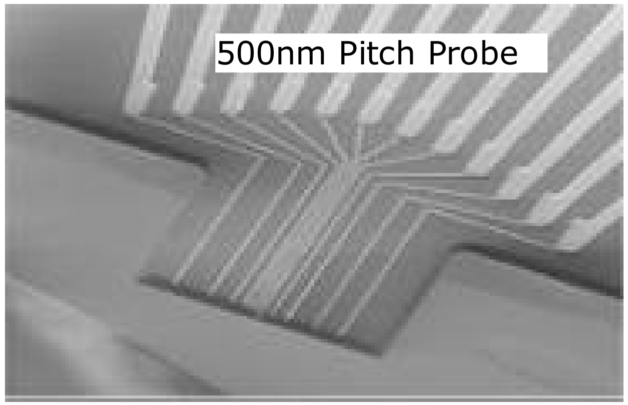




Probe pin pitch app. 1000 times smaller than conventional 4PP

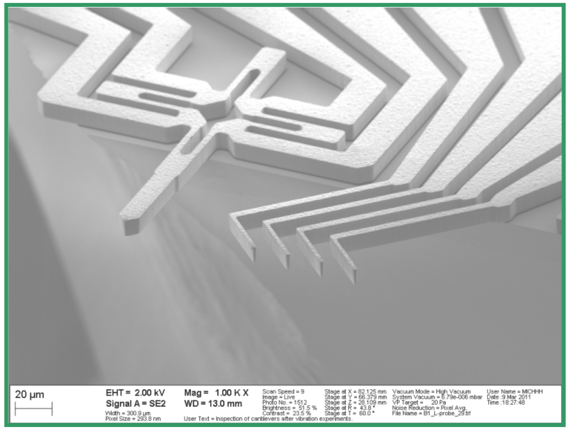
Probe-pin to surface force app. 1.000.000 times smaller than conventional 4PP

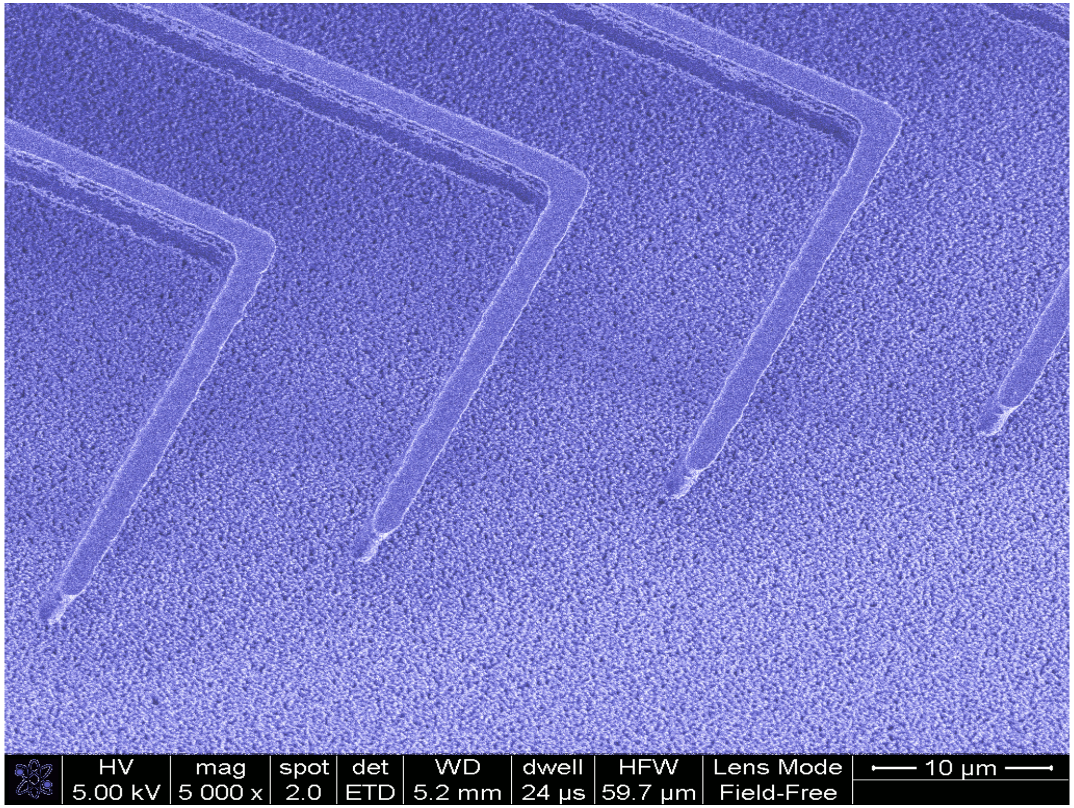




Microscopic Multicantilever Probes M4PP & M12PP

3D Ultra Flexible Microprobe with integrated ”Strain Gauge” cantilever for surface detection.





Static contact to surface during measurement.

- **Can be used in noisy environment**

Increased probe ”lifetime”.

- **More than 2000 measurements per. probe**

No surface layer penetration.

- **< 2nm layers can be measured**

No surface contamination

- **Level much lower than Tier 1 fab. requirements**

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Basic Tool requirements needed to do measure-ments using Microscopic Multicantilever Probes

- High resolution air-bearing X-Y-Z stage for probe positioning (Smallest step size is <50nm)
- Ultra high in-position stability (< 10nm jitter)
- Antivibration system
- X-Y travel range up to 300mm (450mm planned)
- Ultra low noise front end electronics with build-in multiplexer for probe pin configuration setting
- Automatic probe exchange mechanism for use in the fully automatic MicroRSP-A300 tool
- Dual optical system for pattern recognition and probe pin position feedback (resolution <1 um)
- Software with build in functionality to measure Rs and Hall-mobility on small samples and patterned 300mm product wafers

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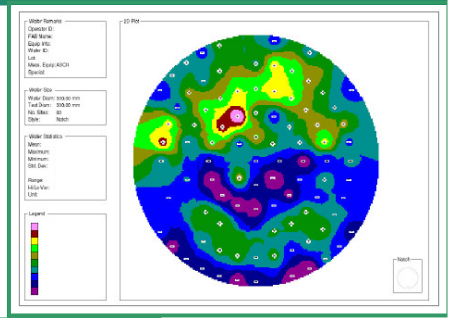
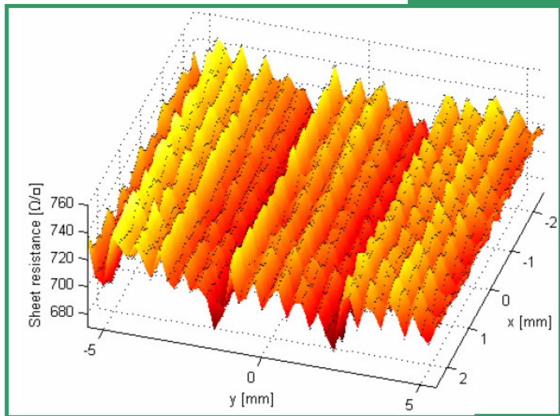
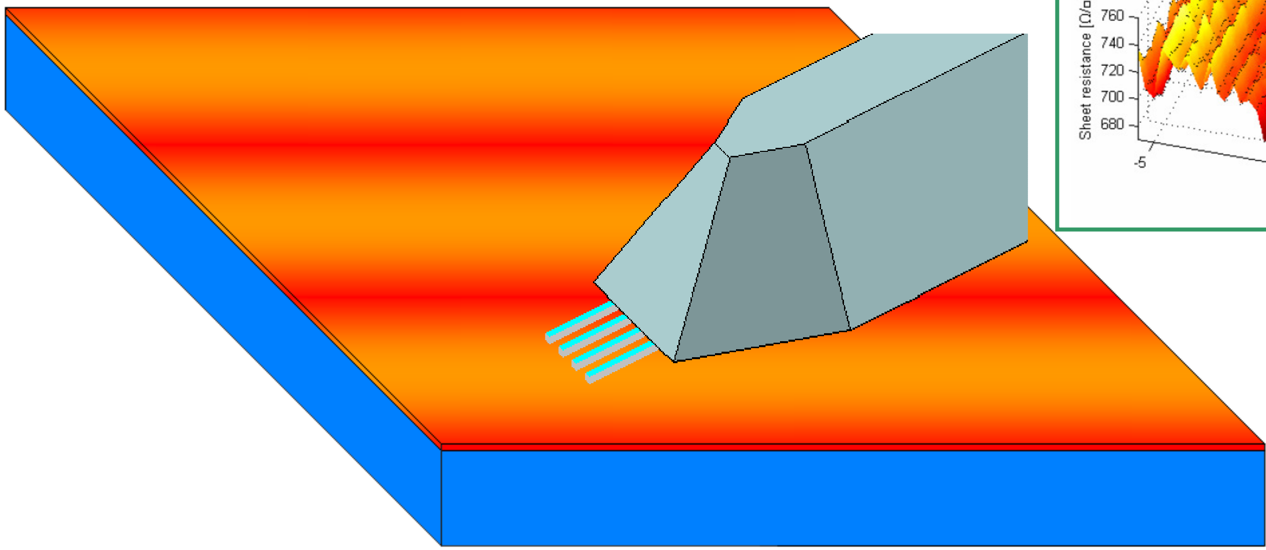
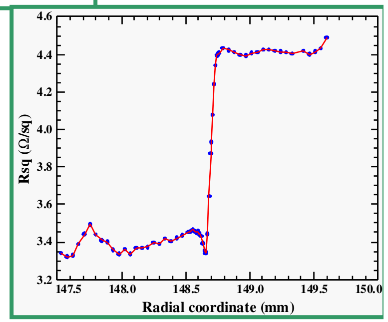
Measurements using Microscopic Multicantilever Probes

- Accurate R_S mapping. (Reproducibility and repeatability: <0.1 %)
- High spatial resolution. (Probe pitch down to 500nm)
- Measurements on ultrathin conducting layers (< 2nm layer thickness)
- No edge exclusion (Zero (0) edge exclusion)









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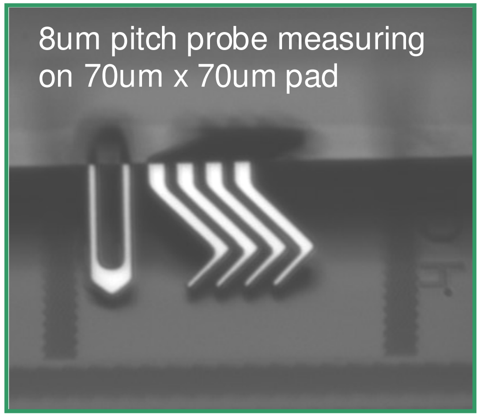
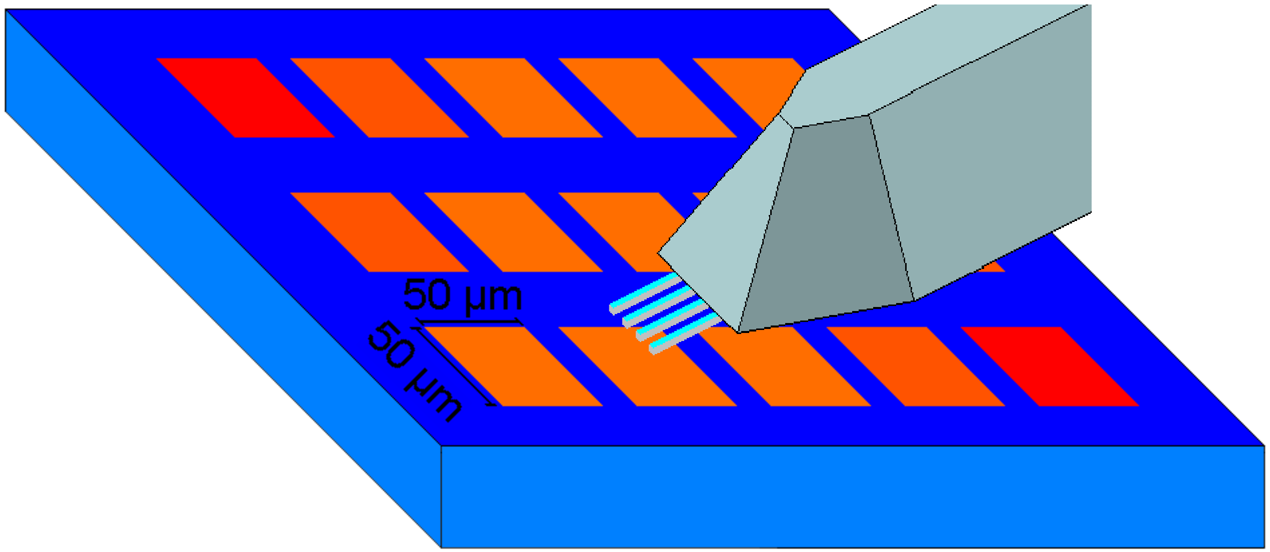
Measurements using Microscopic Multicantilever Probes

- Accurate In-line measurements directly on product wafers.
- Accurate *Rs, Mobility and Active Carrier Density measurements* on small pads.





Automatic probing on pads down to 50um x 50um

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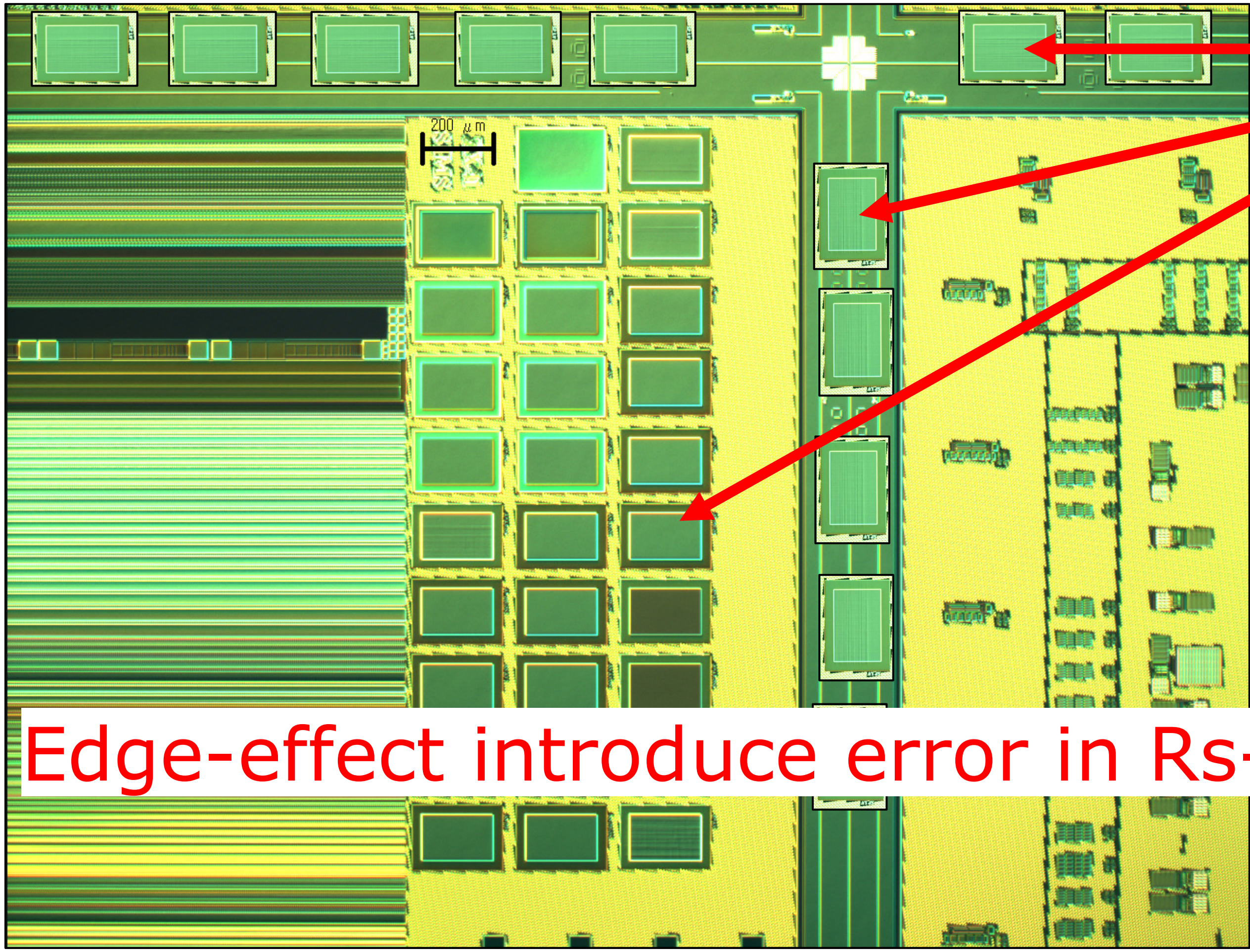
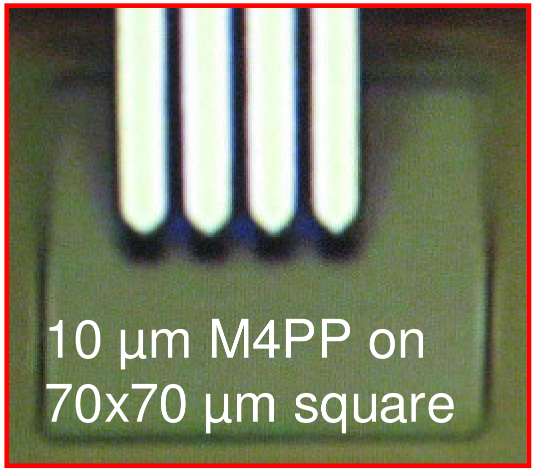
Measurements using Microscopic Multicantilever Probes

Direct Rs and Hall mobility measurements on product wafers



Test pads in scribe lines or test die area



Edge-effect introduce error in Rs-measurement

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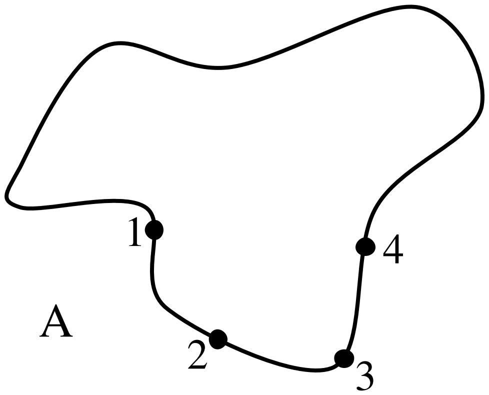
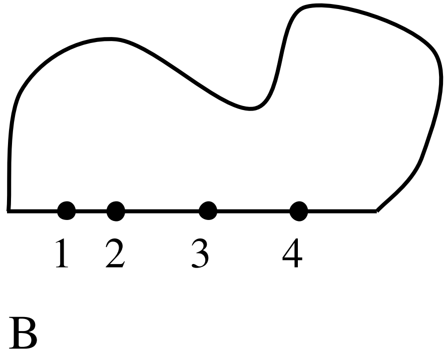
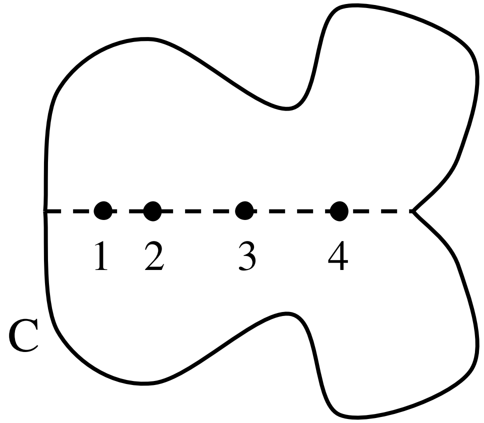
Dual configuration – small samples







Exact measurements on mirror planes!

$$R_a = V_{23}/I_{14}$$
$$R_b = V_{24}/I_{13}$$

$$e^{\frac{\pi R_a}{R_\square}} - e^{\frac{\pi R_b}{R_\square}} = 1$$

L.J. van der Pauw,
Philips Res. Rep. (1958).

$$R_A = V_{23}/I_{14}$$
$$R_B = V_{24}/I_{13}$$

$$e^{\frac{2\pi R_A}{R_\square}} - e^{\frac{2\pi R_B}{R_\square}} = 1$$

R. Rymaszewski, J. Phys. (1969)

S. Thorsteinsson, et al.
Rev. Sci. Instrum. (2009).

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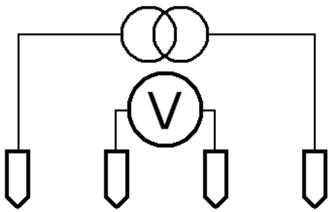
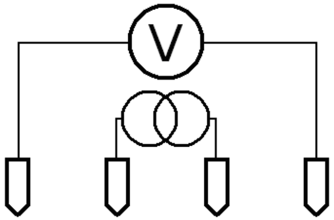
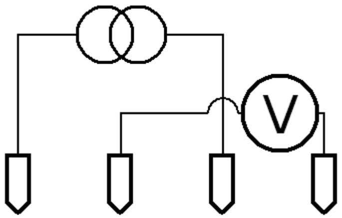
Dual configuration – small samples



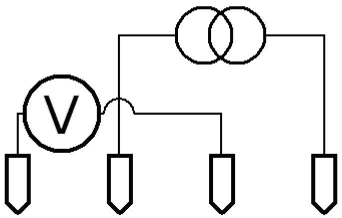
A



A'



B



B'

Resistance difference

$$\Delta R_{AA'} \equiv R_A - R_{A'}$$

Resistance average

$$\overline{R_{AA'}} \equiv \frac{R_A + R_{A'}}{2}$$

Resistance difference

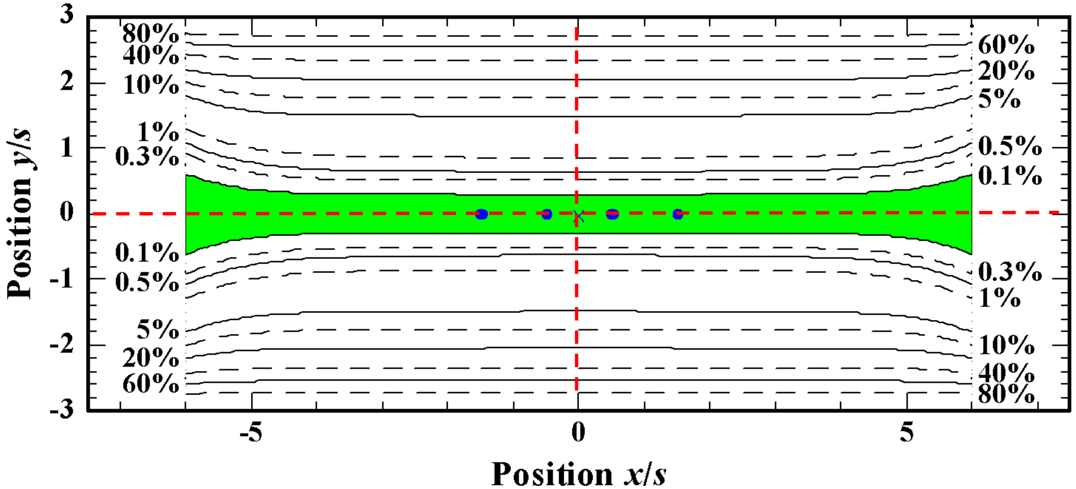
$$\Delta R_{BB'} \equiv R_B - R_{B'}$$

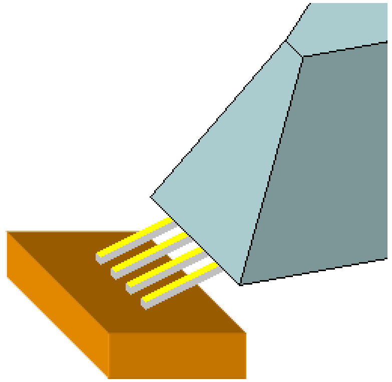
Resistance average

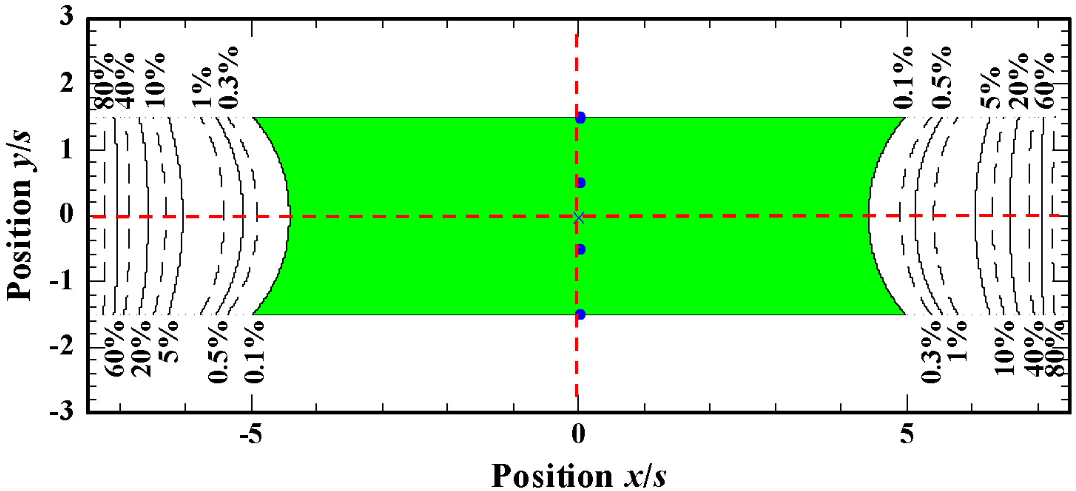
$$\overline{R_{BB'}} \equiv \frac{R_B + R_{B'}}{2}$$

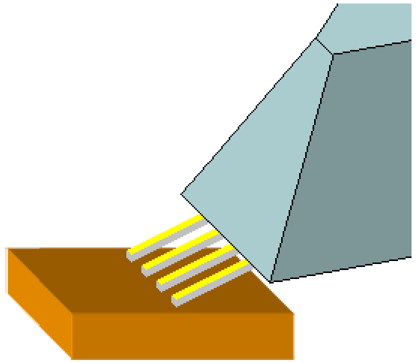
CAPRES A/S

Dual configuration – small samples









S. Thorsteinsson, et al. Rev. Sci. Instrum. (2009).

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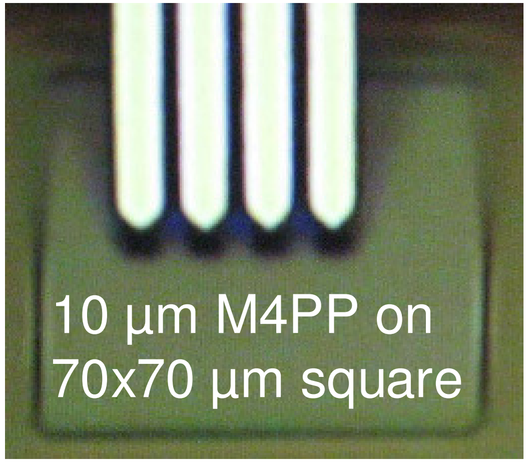
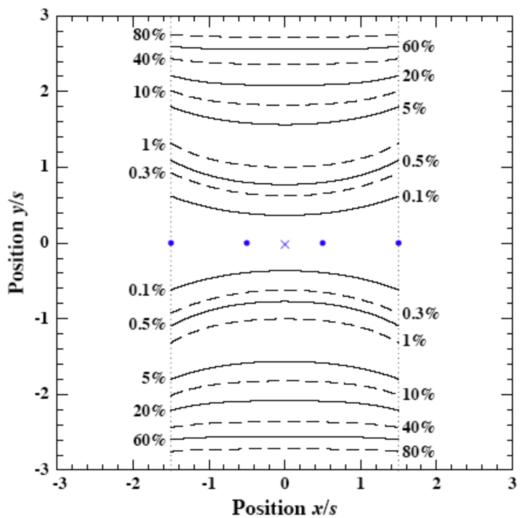
Dual configuration – small samples

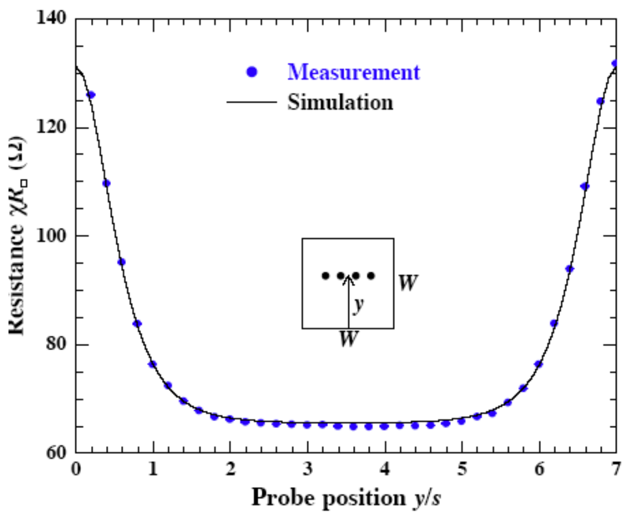
Product Wafer Monitoring

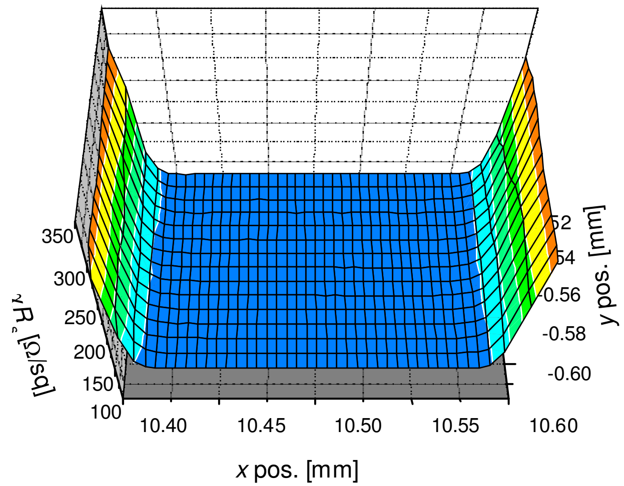
Scribe-line and test area pads

10 µm M4PP using dual-configuration Rs measure-ments with a ± 2.5 µm alignment accuracy, can easily achieve <0.1% offset errors on a 50 x 50 µm pads.









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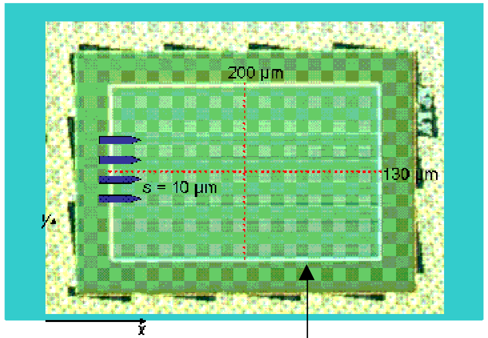
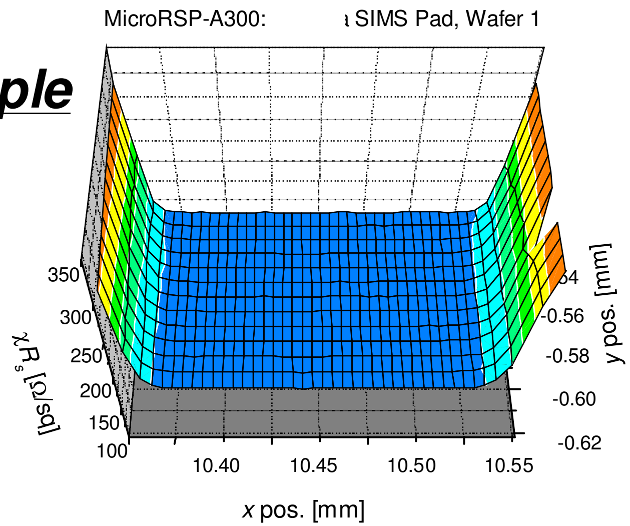
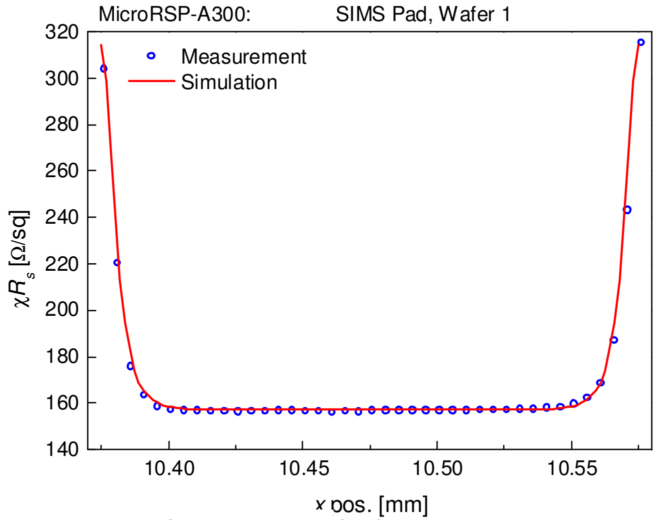
Dual configuration – small samples

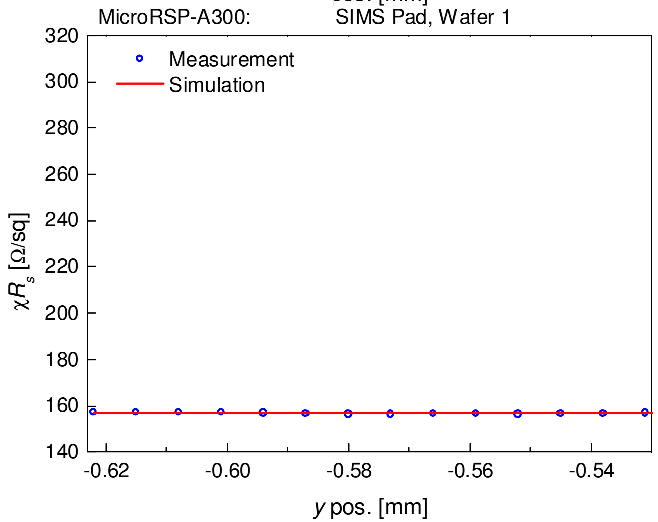
Measurement example



SIMS pad







Rs area map and X-Y line scans measured directly on SIMS pad

Capres' microRSP-A300 tool and probing technology enables direct Rs measurement on pads and small structures on patterned and un-patterned production wafers

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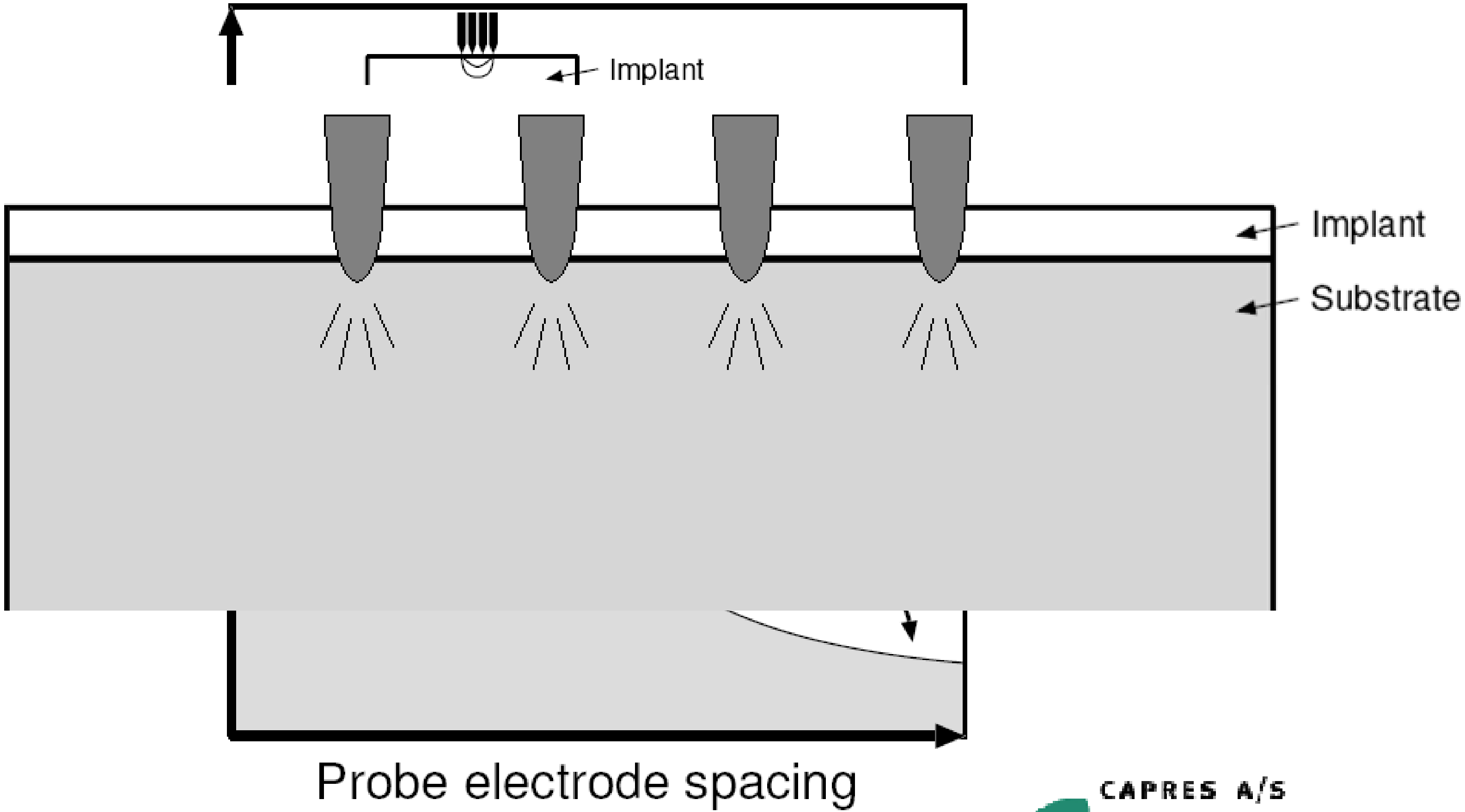
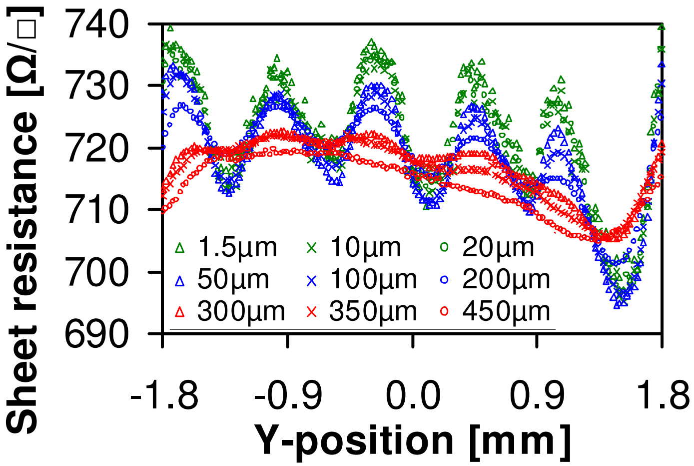
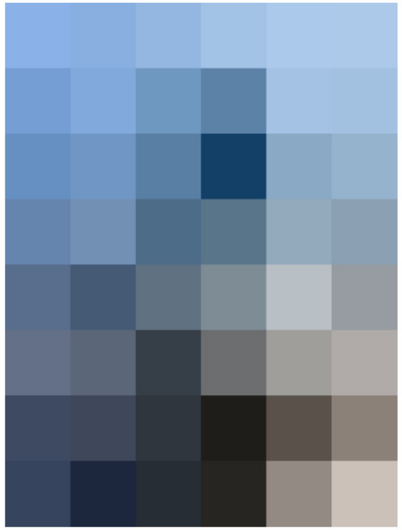
Fundamental limitation
Need soft probes with small probe pin pitch to do correct Rs measurements

- Single conductive sheet
  - Probe penetration
  - Junction leakage



Effect of probe pitch & Resolution matters





6 by 8 pixels

600 by 800 pixels

Macroscopic four-point probes clearly underestimates R_S variations.

Resolution matters

D. H. Petersen et al., JVST B 26, 2008.

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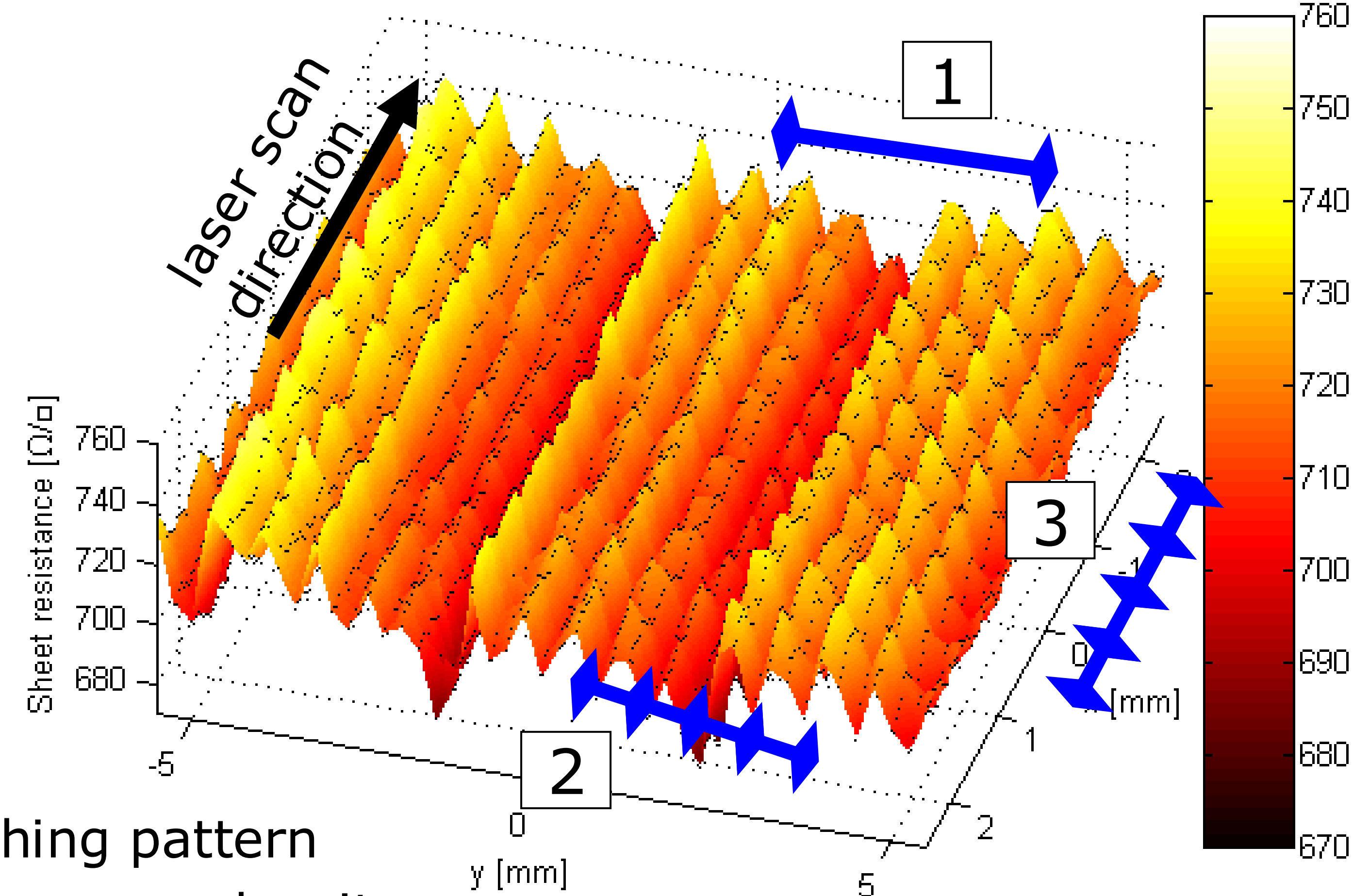
Micro R_S variations



1. Stitching pattern
2. Laser power density
3. Laser power fluctuations

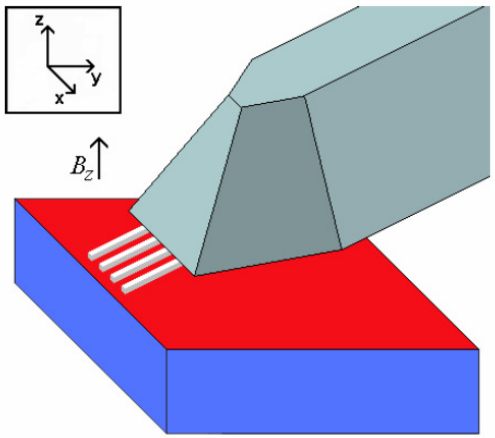
D. H. Petersen et al., JVST B 26, 362 (2008).

W. Vandervorst et al., MRS 2008 Spring meeting (2008).

Hall-mobility
Measure Rs using a collinear 4PP and extract Mobility and Active Carrier Density

$$R_S = \frac{1}{e\overline{\mu}_H N_{HS}}$$

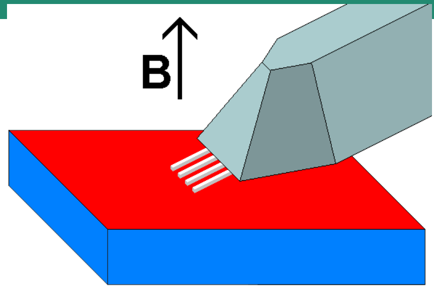
$$N_{HS} = \left|\frac{B_z I}{eV_H}\right| \qquad \overline{\mu}_H = \left|\frac{V_H}{B_z R_S I}\right| \qquad \frac{V_H}{I} \equiv \frac{B_z}{ZeN_{HS}}$$



Notation

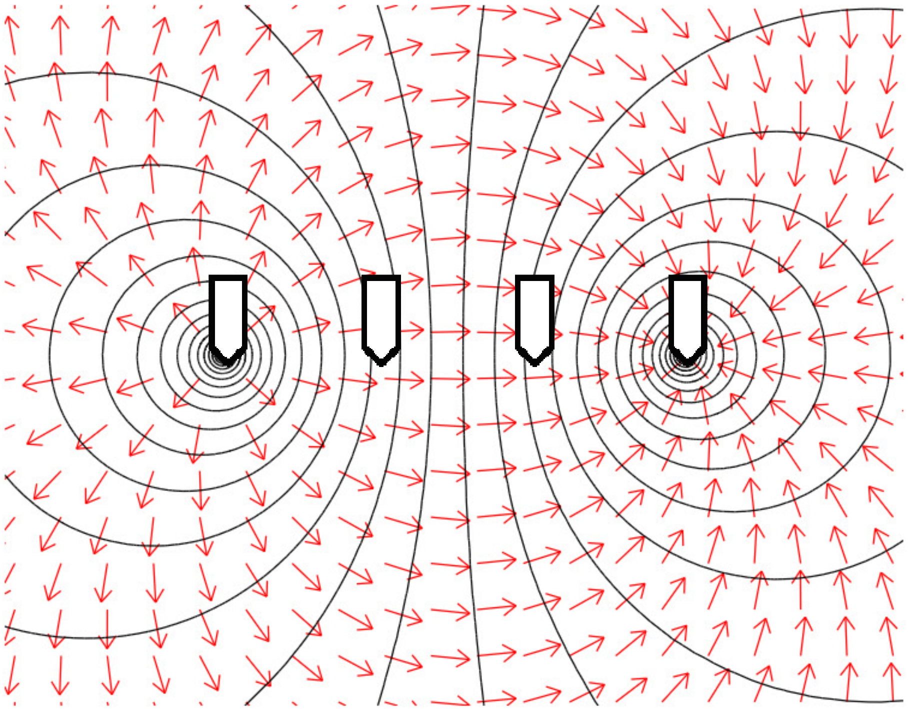
e = unit charge. (constant)
Z = carrier charge (Z = ±1).
B_z= magnetic flux density. (constant)
N_{HS} = Hall Sheet Carrier Density.
$\overline{\mu}_H$= Average Hall Mobility.
VH = Measured Hall Voltage
I = Applied measurement current

Infinite sheet: No Hall Effect



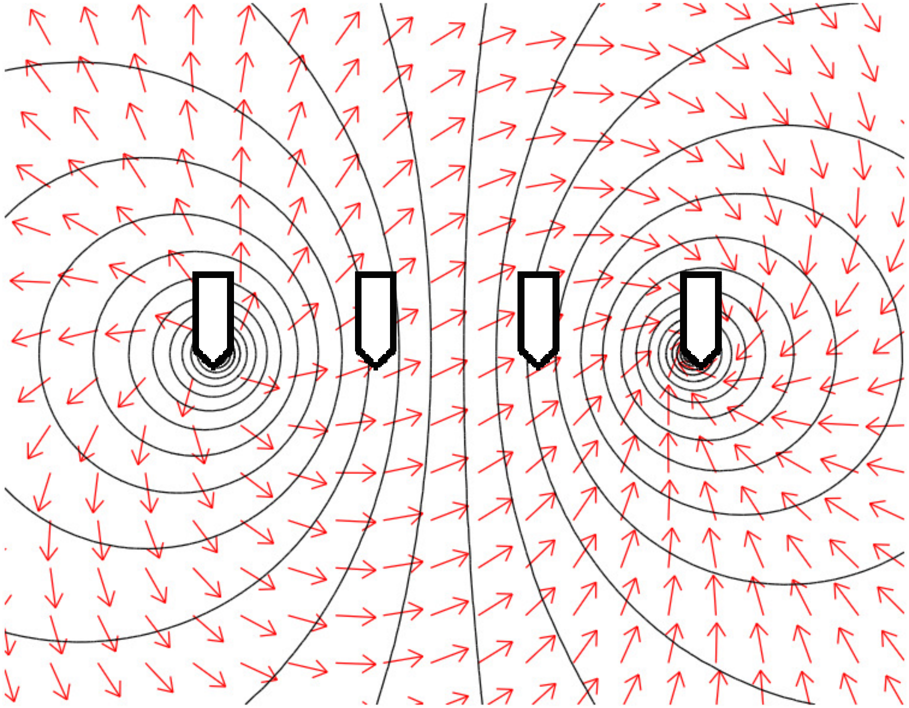
$B = 0$

Purely radial current

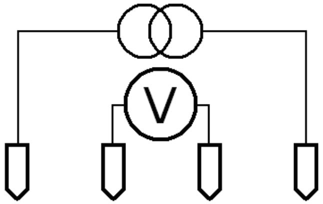


$B \neq 0$

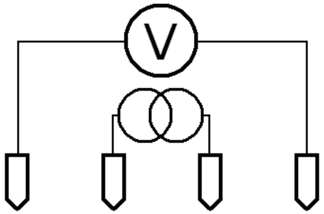
Tangential current



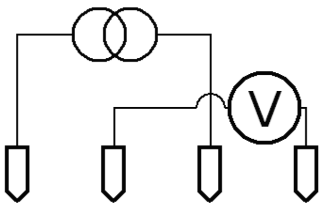
Micro Hall effect



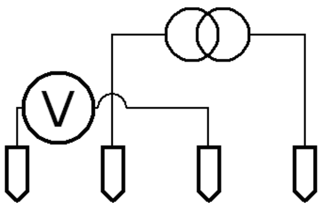
A



A'



B



B'

Resistance difference

$$\Delta R_{AA'} \equiv R_A - R_{A'} = 0$$

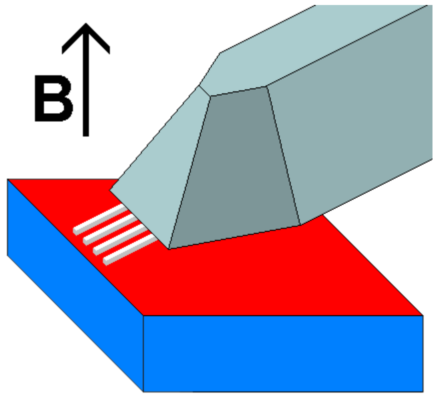
$$\Delta R_{BB'} \equiv R_B - R_{B'} = c_H R_H$$

Resistance average

$$\overline{R_{AA'}} \equiv \frac{R_A + R_{A'}}{2} = c_A R_S$$

$$\overline{R_{BB'}} \equiv \frac{R_B + R_{B'}}{2} = c_B R_S$$

D.H. Petersen, et al., J. Appl. Phys. (2008).



Mobility

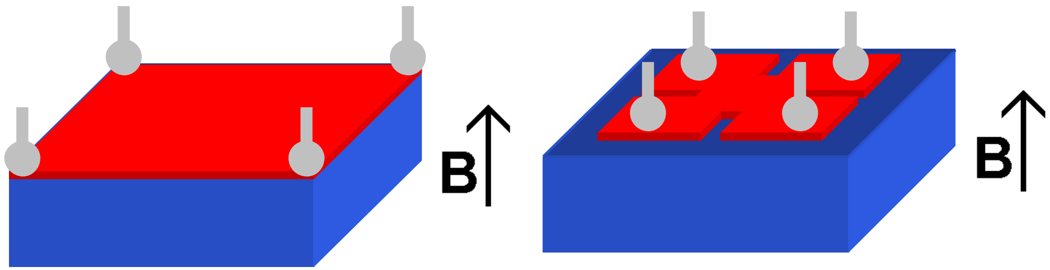
$$\overline{\mu} = \frac{ZR_H}{\overline{r}_H R_S B_z}$$

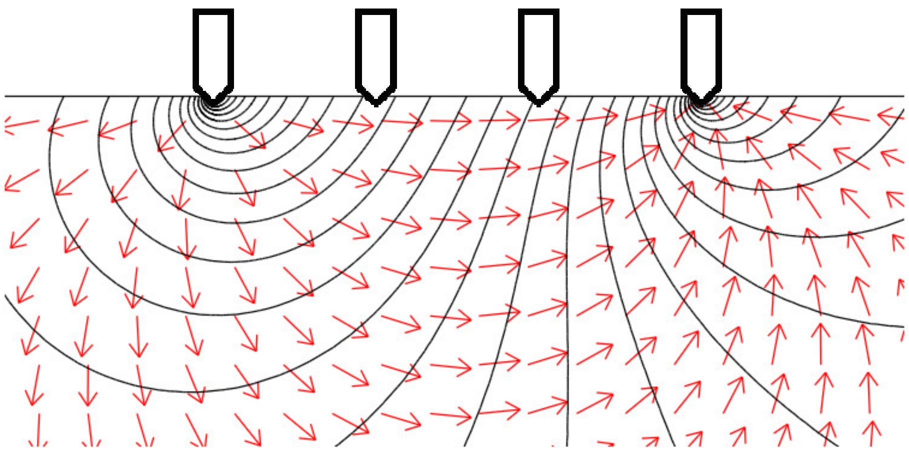
Sheet carrier density

$$N_S = \frac{\overline{r}_H B_z}{ZeR_H}$$

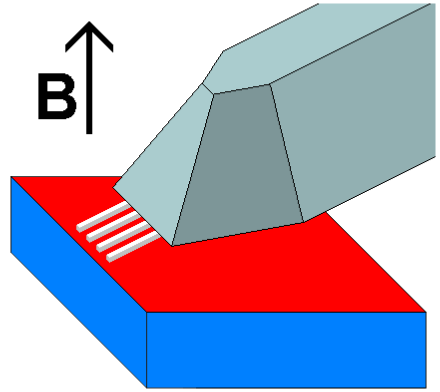
Single barrier: Hall effect

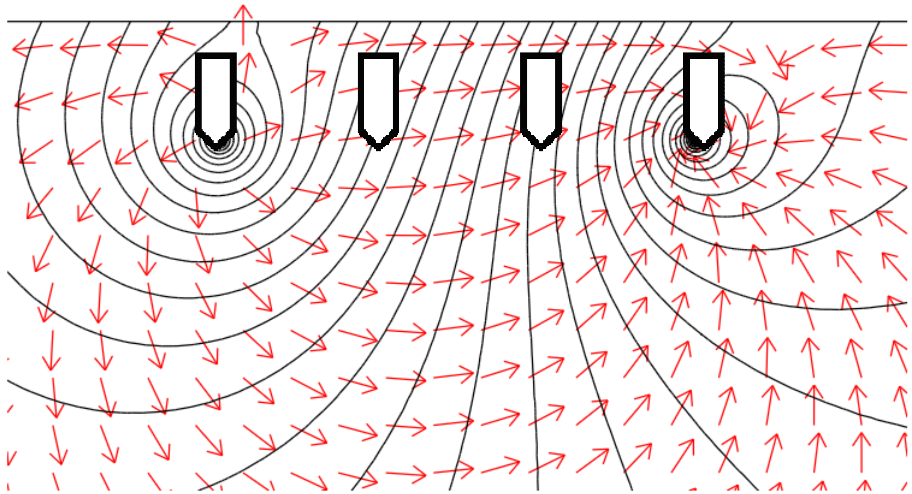
Conventional Hall effect (van der Pauw)



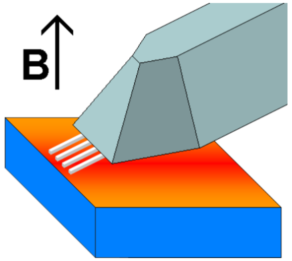


Micro Hall effect



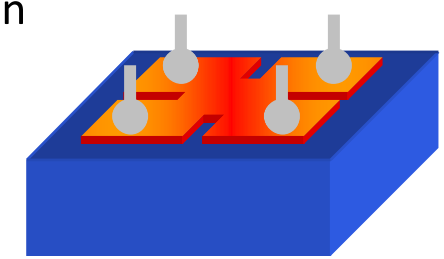


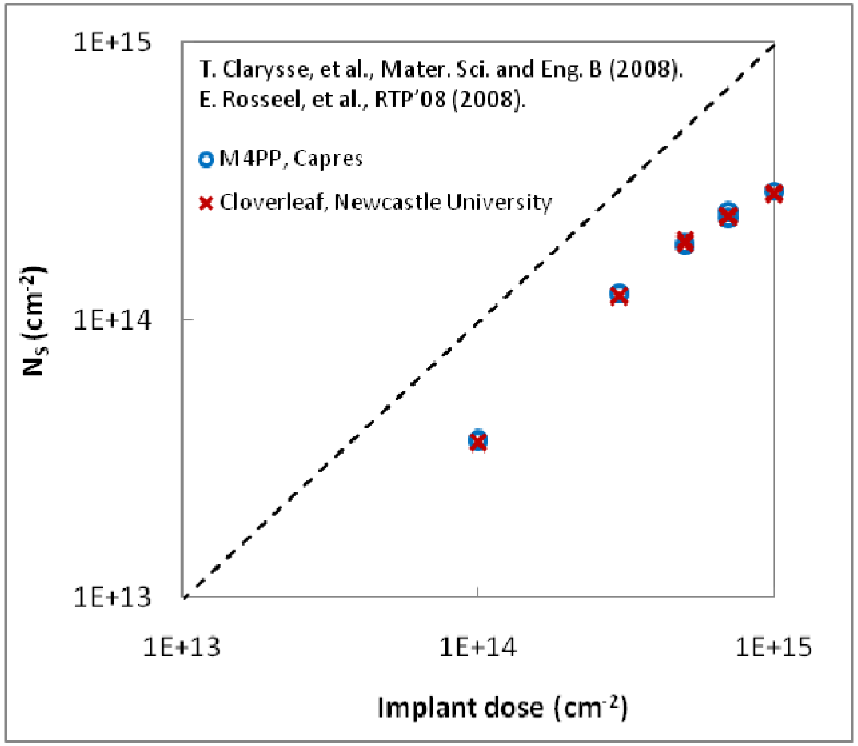
M4PP vs. Cloverleaf patterned Hall

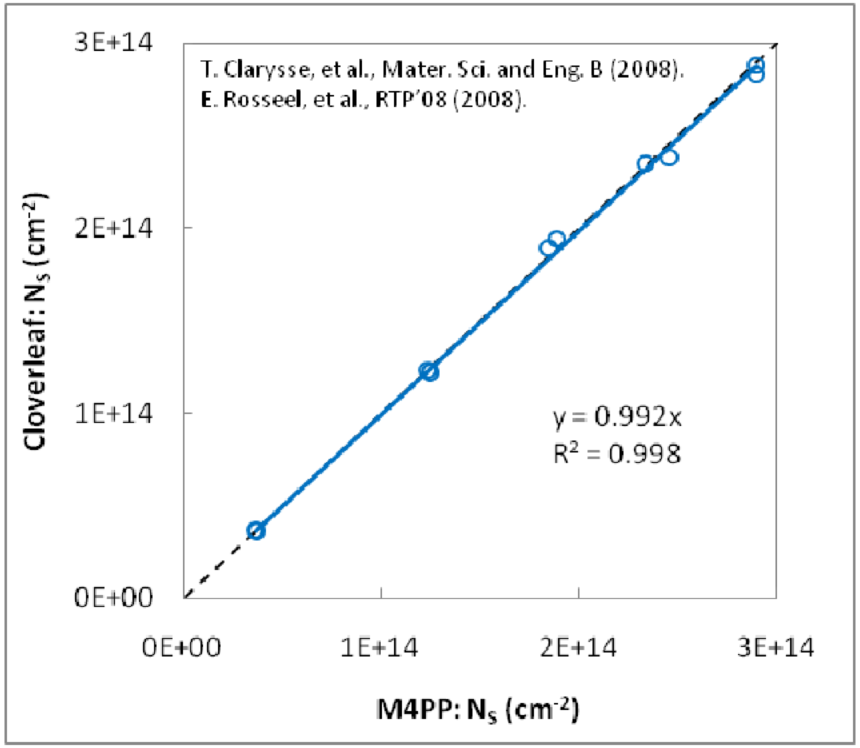


Millisecond laser annealed ultra shallow junction
B doped c-Si (n-type), r_H = 0.8

Figures using data from cited references





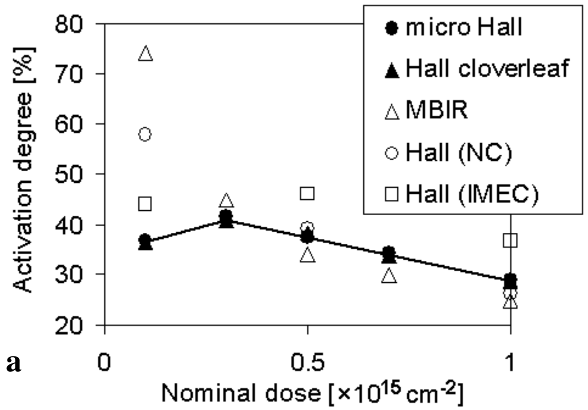


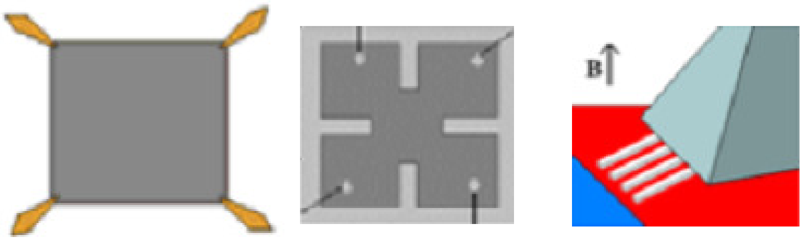
Micro Hall effect

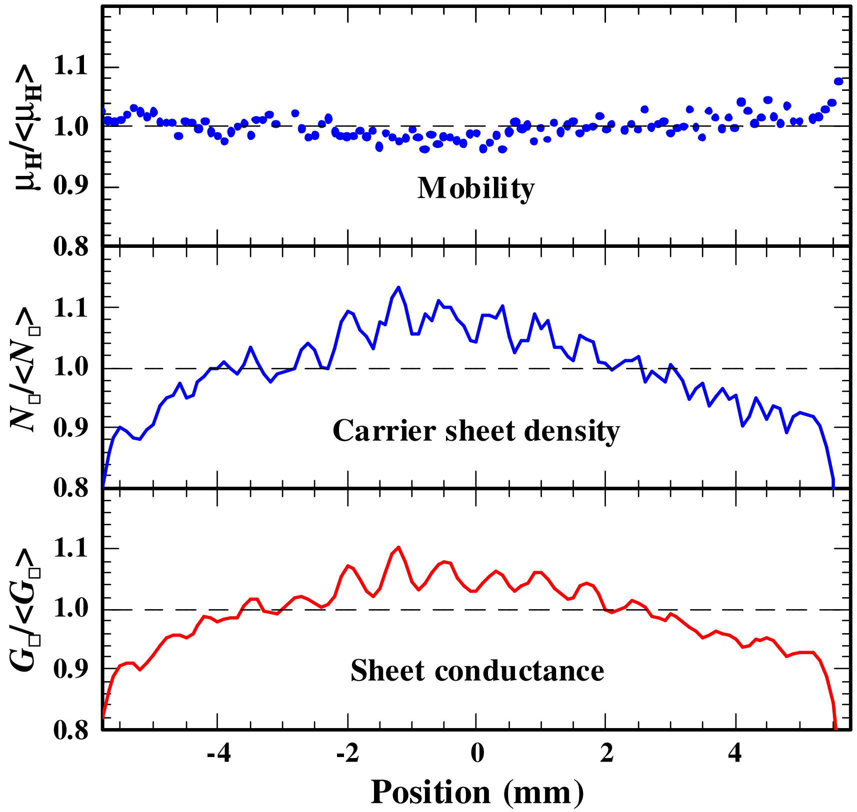
- Reproducibility <1.5%
- Repeatability <1%

D.H. Petersen, et al., J. Appl. Phys. (2008).

D.H. Petersen, et al., RTP’08 (2008).





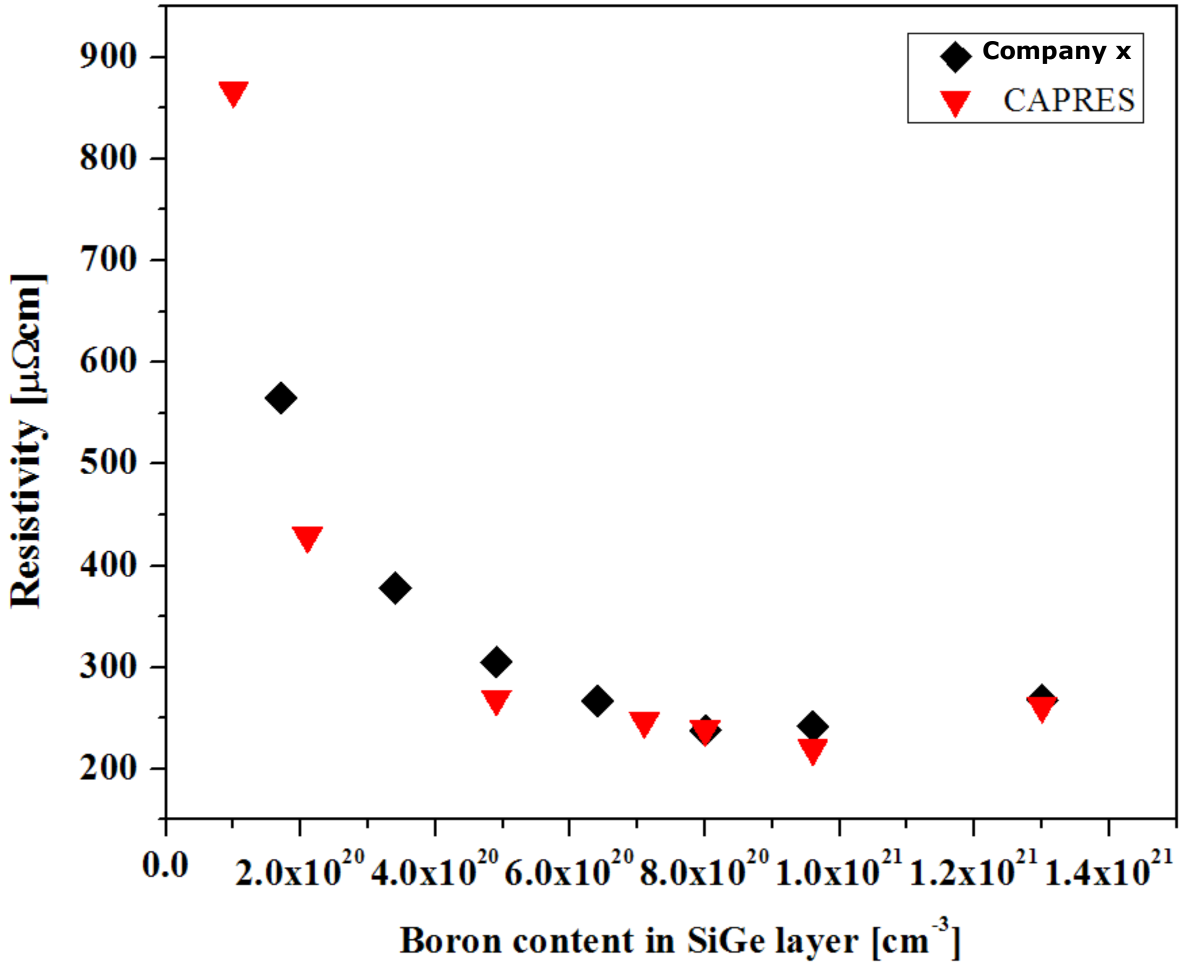


E. Rosseel, et al., RTP’08 (2008).

T. Clarysse, et al., Mater. Sci. and Eng. B (2008).

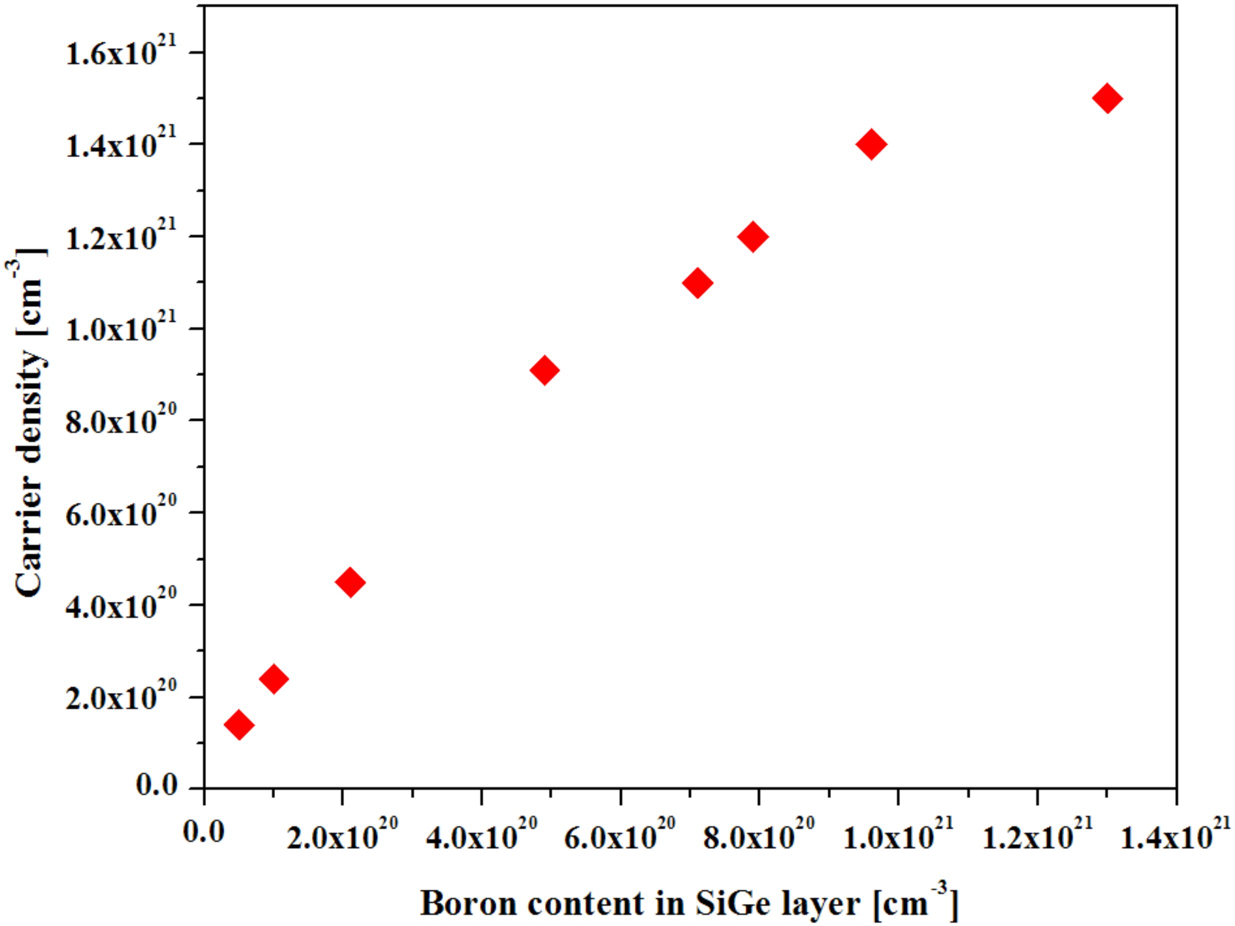
CAPRES A/S

Direct microRs- and micro-Hall mobility measurements on Boron and Carbon Co-doped 60% SiGe layers



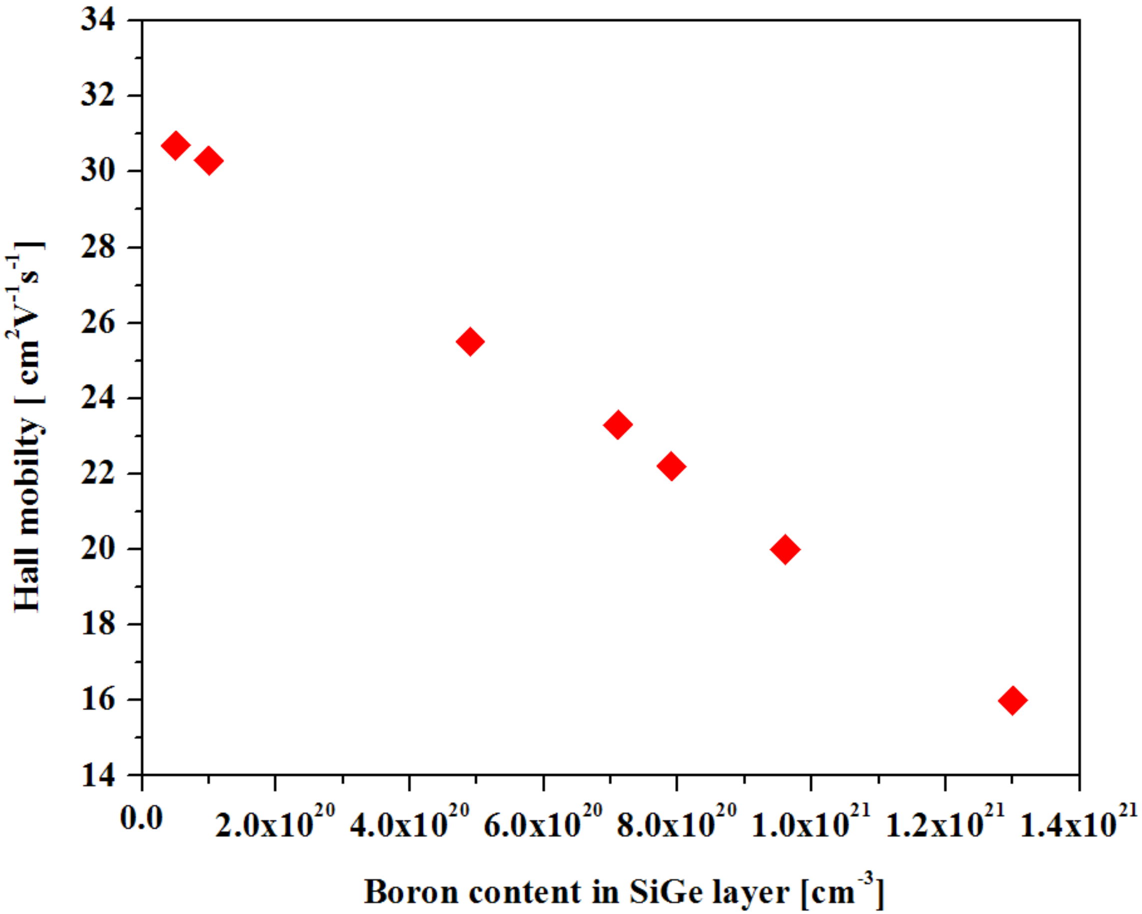
CAPRES A/S

Direct microRs- and micro-Hall mobility measurements on Boron and Carbon Co-doped 60% SiGe layers

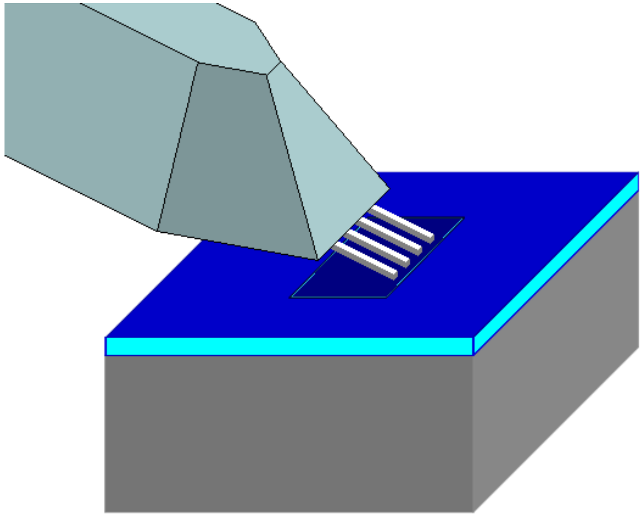


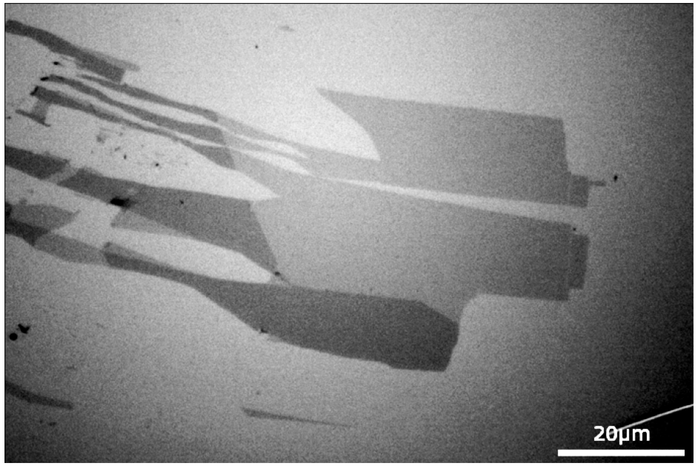
CAPRES A/S

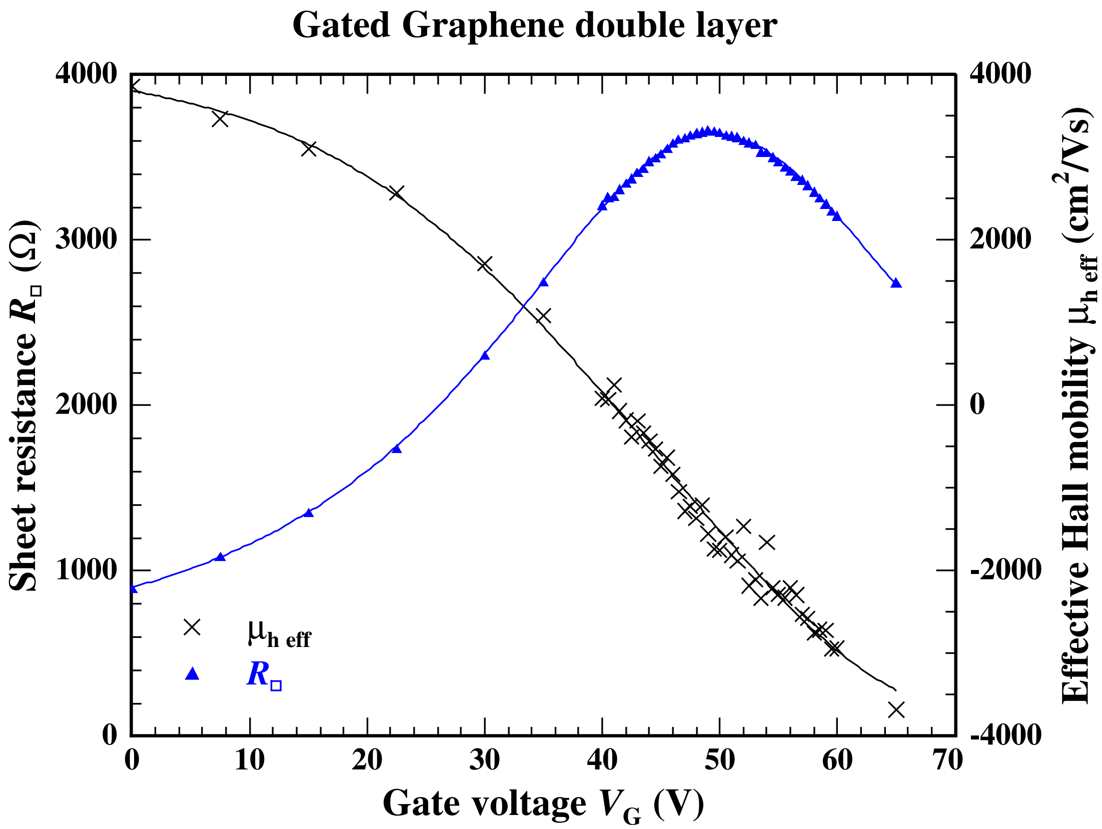
Direct microRs- and micro-Hall mobility measurements on Boron and Carbon Co-doped 60% SiGe layers



Micro Hall effect







CAPRES A/S

Capres Fact-Sheet

- Established in 1999. VC-Fonded.
- More than 45 Fully- and Semi-automatic Tools installed World Wide
- First Fully Automatic MicroRSP-A300 tool installed in 2010
- Six Fully Automatic MicroRSP-A300 tools will be installed in 2012.
- New Semiautomatic 300mm tool including both Rs and Hall-mobility measurement capability ready and installed
- Next application will be direct Leakage Current measurements using the collinear micro-probe. Will be presented at IIT 2012 in Spain

CAPRES A/S

Conclusion

By using M4PP in combination with a high resolution positioning system it is possible to:

- **Do direct Rs measurments on small samples**

  Enables accurate Rs measurements on e.g scribeline pads
- **Measure micron scale variation in Rs**

  Enables optimization of the very local sheet resistance
- **Micro Hall effect**

  Enables fast measurement of the Active Carrier Density and Mobility using the collinear M4PP
- **Repeatability, reproducibility**
  - R_S: $\sigma < 0.1$ %
  - R_H: $\sigma < 1$ %

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Polarbear at weatherstation Danmarkshavn Northeast Greenland

Photo: Peter Folmer Nielsen

Thank you for your attention

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COPENHAGEN APPLIED RESEARCH