SHEET RESISTANCE AND MOBILITY MEASUREMENTS WITH MICRO-PROBES: FROM PLANAR TO 3D TECHNOLOGIES

RESISTANCE MEASUREMENTS IN FRONT END OF LINE?

- improving transistor performance

Adapted from A. Schulze, PhD thesis (KULeuven, 2013)
RESISTANCE MEASUREMENTS IN FRONT END OF LINE?

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- improving transistor performance $\rightarrow$ reduce $R_{\text{series}}$

$$R_{\text{series}} = R_{\text{source}} + R_{\text{drain}} + 2R_{\text{contact}} + R_{\text{channel}}$$
RESISTANCE MEASUREMENTS IN FRONT END OF LINE?

- Improving transistor performance → reduce $R_{\text{series}}$
- **Today**: $R_{\text{contact}}$ dominant → increase carrier concentration $N$

Adapted from A. Schulze, PhD thesis (KULeuven, 2013)
FROM A FOUR-POINT MEASUREMENT TO CARRIER CONCENTRATION

From sheet resistance $R_s$ to resistivity $\rho$

\[ R_s = \frac{\rho}{t} \]

- $R_s \rightarrow$ resistivity $\rho$
From sheet resistance $R_s$ to resistivity $\rho$

$$R_s = \frac{\rho}{t}$$

doped layer

Substrate

From resistivity $\rho$ to carrier concentration $N$

$$\rho = \frac{1}{(q\mu N)}$$

Assumption: mobility $\mu$ only depends on $N$ $\Rightarrow$ $N$ can be extracted

FROM A FOUR-POINT MEASUREMENT TO CARRIER CONCENTRATION
Advantages of micro-probes, i.e. with micron-scale pitch \( d \):  
• High-accuracy sheet resistance on ultra-shallow layers  
• Sheet resistance on patterned wafers  
• Mobility/carrier concentration (microHall) on patterned wafers  
• Resistance of nm-wide conductive lines
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• Resistance of nm-wide conductive lines
M4PP VS STANDARD 4PP

Samples from Dr. A
(undoped substrate)

Samples from Dr. B
(doped substrate)
M4PP VS STANDARD 4PP

Samples from Dr. A (undoped substrate)

Samples from Dr. B (doped substrate)
REQUIREMENTS FOR AN ACCURATE SHEET RESISTANCE MEASUREMENT

- Standard 4pp requires:
  - opposite doping type (p vs n) in the substrate $\rightarrow$ high $\rho_{dep}$
  - lowly doped substrate $\rightarrow$ wide depletion region $W_{dep}$
Requirements for an accurate sheet resistance measurement

- Standard 4pp requires:
  - opposite doping type (p vs n) in the substrate $\rightarrow$ high $\rho_{dep}$
  - lowly doped substrate $\rightarrow$ wide depletion region $W_{dep}$
- M4pp more relaxed on substrate doping

$D.C.\ Worledge\ et\ al,\ Appl.\ Phys.\ Lett.\ 83,\ 84\ (2003)$
**M4PP VS STANDARD 4PP**

**Samples from Dr. A** (undoped substrate)

- $R^{4pp}_{dep} \sim 10 \text{kOhm}$
- $R^{m4pp}_{dep} \sim 1 \text{MOhm}$

**Samples from Dr. B** (doped substrate)

- $R^{4pp}_{dep} \sim 100 \text{ Ohm}$
- $R^{m4pp}_{dep} \sim 10 \text{kOhm}$

**M4pp is accurate also on doped substrates**

standard 4pp measures substrate
• High-accuracy sheet resistance on ultra-shallow layers
• Sheet resistance on patterned wafers
• Mobility/carrier concentration (microHall) on patterned wafers
• Resistance of nm-wide conductive lines
SAMPLE FROM DR. C: PATTERNED WAFER WITH SMALL PAD

- 4pp does not fit into small pad
- limited sampling volume (~24x20 $\mu$m$^2$) $\Rightarrow$ only small pads needed
SAMPLE FROM DR. C: PATTERNED WAFER WITH SMALL PAD

m4pp: $d_{\text{inj}} = 24 \, \mu m$

- Doped layer
- Substrate
- Oxide

- 4pp does not fit into small pad but m4pp does
- Limited sampling volume ($\sim 24 \times 20 \, \mu m^2$) → only small pads needed

Standard 4pp: $d_{\text{inj}} \sim 1 \, \text{mm}$

- Doped layer
- Substrate
- Oxide

4pp does not fit into small pad but m4pp does
limited sampling volume (~24x20 µm²) → only small pads needed
• High-accuracy sheet resistance on ultra-shallow layers
• Sheet resistance on patterned wafers
• Mobility/carrier concentration (microHall) on patterned wafers
• Resistance of nm-wide conductive lines
PROBLEM WITH DR. D’S SAMPLES: SATURATION OF CARRIER CONC.?

• Saturation of resistivity as total [B] increases?
PROBLEM WITH DR. D’S SAMPLES: SATURATION OF CARRIER CONC.?

- Saturation of resistivity as total [B] increases → Saturation of carrier concentration?
- Mobility not degraded when increasing [B] from 5e20 to 1e21 cm⁻³?
From sheet resistance $R_s$ to resistivity $\rho$

\[ R_s = \frac{\rho}{t} \]

From resistivity $\rho$ to carrier concentration $N$

\[ \rho = \frac{1}{q\mu N} \]

- $\mu$ also depends on defect density, layer thickness, inactive dopants etc $\rightarrow$ measure $\mu$
CONVENTIONAL HALL MEASUREMENTS

- Magnetic field $B$
- Van der Pauw configuration
- cm probe spacing
  $\Rightarrow$ Leakage 😞
CONVENTIONAL HALL MEASUREMENTS

- Magnetic field $B$
- Van der Pauw configuration
- cm probe spacing $\rightarrow$ Leakage 😞

$V_{\text{hall}} \rightarrow$ mobility

$F_{\text{Lorentz}}$

Hall voltage with 4 aligned probes?
REQUIREMENTS FOR A MICRO-HALL MEASUREMENT

- **Insulating edge:**
  - non-zero Hall signal (asymmetry)

Electrostatic potential (V)

D.H. Petersen et al.,
REQUIREMENTS FOR A MICRO-HALL MEASUREMENT

- **Insulating edge:**
  - Non-zero Hall signal (asymmetry)
  - 7-point probe:
    - M4PP at two different pitches (measurement of distance \( d \) to edge)

MICROHALL VS HALL: THICK InGaAs LAYERS

MicroHall nicely agrees with conventional Hall on thick layers.
B-doped Ge epi with different [B] in n-Ge buffer.

Hall mobility (cm$^2$/V/s) vs. SIMS [B] (cm$^{-3}$)

Carrier concentration (cm$^{-3}$) vs. SIMS [B] (cm$^{-3}$)

Hall mobility must be measured for an accurate determination of carrier concentration.

→ Carrier concentration in Dr. D’s samples does NOT saturate.
MICROHALL MEASUREMENTS ON PATTERNED WAFERS

Si:B (5 KV, 3E15CM⁻²) + SPIKE ANNEAL (1035°C, 1.5 S)

Rs (ohm/sq)  
Hall mobility (cm²/V/s)  
Hall sheet carrier density (cm⁻²)

Unique capabilities of Hall measurements on patterned wafers
• High-accuracy sheet resistance on ultra-shallow layers
• Sheet resistance on patterned wafers
• Mobility/carrier concentration (microHall) on patterned wafers
• Resistance of nm-wide conductive lines
Questions of Prof. V:
1. Can you measure on nm-wide lines?
2. Is $R_s$ dimension-dependent?
All 4 probes on fin: Low contact resistance $\rightarrow$ short RC constant

Freq. = 13 Hz

Phase shift = 0
PROBES IN CONTACT WITH THE FIN?

All 4 probes on fin: Low contact resistance $\rightarrow$ short RC constant

1 probe on oxide: high contact resistance $\rightarrow$ long RC constant

1st sanity check: $\text{Phase}_I - \text{Phase}_V = 0 \rightarrow$ 4 probes on the conductive fin

Freq. = 13 Hz
MICRO FOUR-POINT PROBE MEASUREMENT IN CONFINED VOLUME


Configuration A:

Potential distribution inside the fin

- fin resistance between pins 2 and 3 is measured
MICRO FOUR-POINT PROBE MEASUREMENT IN CONFINED VOLUME


Potential distribution inside the fin

• fin resistance between pins 2 and 3 is measured
MICRO FOUR-POINT PROBE MEASUREMENT IN CONFINED VOLUME


Configuration A:

Potential distribution inside the fin

Configuration B:

- fin resistance between pins 2 and 3 is measured
- Same resistance measured in a and b configurations ($R_a/R_b = 1$)

$\frac{R_a}{R_b}$ RATIO AND DIMENSIONALITY OF THE CURRENT FLOW


- $\frac{R_a}{R_b}=1.00 \rightarrow$ 1D current flow (fin)
- $\frac{R_a}{R_b}=1.26 \rightarrow$ 2D current flow (blanket)
- Information about leakage can be extracted based on $\frac{R_a}{R_b}>1$
SAMPLE OF PROF.V: B-IMPLANTED SI FINS

B (5 kV, $3 \times 10^{15}$ cm$^{-2}$) annealed @ 450ºC, 15’

- 80x80 µm$^2$
- 10 fins of 500 nm width
- 10 fins of 20 nm width

Probe scan direction

Rs=314 ohm/sq
B-IMPLANTED FINS: EXPERIMENTAL

\[ \frac{R_a + R_b}{2} \text{(ohm)} \]
B-IMPLANTED FINS: EXPERIMENTAL

- All widths captured
- Measured resistance increases with decreasing width
B-IMPLANTED FINS: EXPERIMENT VS THEORY

- Resistor model fits the measured data $\rightarrow$ resistivity $\pm$ independent from dimension (mostly geometrical confinement)
B-IMPLANTED FINS: EXPERIMENT VS THEORY

- Resistor model fits the measured data \(\rightarrow\) resistivity +/- independent from dimension (mostly geometrical confinement)
- Annealing lowers the measured fin resistance

\[ R = R_{\text{pad}} \times \frac{d_{23}}{W} \]

\( R_{\text{pad}} = 314 \text{ ohm/sq} \)

\( R_{\text{pad}} = 59 \text{ ohm/sq} \)

\( R_{\text{pad}} = 135 \text{ ohm/sq} \)

- \( T = 450 \, ^\circ \text{C}, 15' \)
- \( T = 1150 \, ^\circ \text{C}, 7 \) laser scans
- \( T = 1250 \, ^\circ \text{C}, 7 \) laser scans
Answer to Prof. V’s question:

- Long low-T anneal: dimension-dependent $R_s$  
  $\Rightarrow$ Depletion effect, degraded mobility, defects, dopant diffusion?

- Laser anneal $\Rightarrow R_s \sim$ independent from width
CONCLUSION: ADVANTAGES OF MICRO-PROBES

• **Accurate** sheet resistance measurements:
  o short distance between probes limits current leakage into substrate

• Measurements in small pads and hence **patterned wafers**
  o short distance between probes limits sampling volume

• **Mobility/carrier concentration** measurements on patterned wafers
  o Measurement along insulating edge and under magnetic field
  o Mobility and hence carrier concentration can be measured

• Sheet resistance of **nm-wide semiconducting lines**:
  o Short distance between probes simplifies alignment
  o Dimension dependent Rs is measured
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