2. Basic Electrical Parameters of Semiconductors: 
Sheet Resistivity, Resistivity and Conduction Type

2.1 Objectives
1. Familiarizing with experimental techniques used for the measurements of electrical properties of semiconductors.
3. Measurements of conductivity of high-ohmic intrinsic and compensated semiconductors by resistance method.
4. Determination of conductivity type of semiconductors by “Hot-Probe” method.

2.2 Principles

2.2.1 The van der Pauw Method
The van der Pauw method is a technique commonly used to measure resistivity $\rho$, sheet resistance $R_s$, concentration of majority charge carriers $n, p$ (electrons, or holes) and their sign as well as mobility $\mu$ of charge carriers of semiconductor. The power of the van der Pauw method lies in its ability to accurately measure the properties of a thing sample of arbitrary shape. The method was first propounded by Leo J. van der Pauw in 1958.

In order to use the van der Pauw method, the thickness of sample $t$ must be much less than its width and length. It is preferable that the sample is symmetrical (Fig. 1).

*Fig. 1.* Two common types of van der Pauw samples: clover leaf and square. Each sample has four symmetrical electrical contacts.

The correct measurements require that four ohmic contacts are attached on the boundary of the sample. The contacts must be much smaller than the distance between them. In addition, the
leads connected to the contacts must be made of the same batch of wire to minimize thermoelectric effects. For the same reason, all four contacts should be of the same material.

The contacts are numbered from 1 to 4 in a counter-clockwise order, beginning at the top-left contact. The voltages measured between contacts and the currents flowing between them are defined as following. For instance, the current $I_{12}$ is a positive DC current injected into contact 1 and taken out of contact 2, and is measured in amperes. The voltage $V_{34}$ is a DC voltage measured between contacts 3 and 4 (i.e. $V_4 - V_3$) with no externally applied magnetic field, measured in volts.

### 2.2.2. Resistivity measurements

The average resistivity $\rho$ of a sample can be calculated as a product of its sheet resistance $R_S$ and thickness $t$:

$$\rho = R_S \cdot t.$$

$R_S$ can be found measuring two van der Pauw resistances along two perpendicular sides of square sample. Van der Pauw resistance is a ratio of the voltage applied across one edge of sample over the current generated along the opposite edge of the sample. For instance, $R_{41,23}$ is measured as voltage $V_{23}$ over current $I_{41}$ (Fig. 2).

$$R_{41,23} = \frac{V_{23}}{I_{41}}.$$  

![Diagram](image)

Fig. 2. Example of measuring van der Pauw resistance. Voltage is applied along one side, while the generated current is measured along the opposite side. Picture shows the measurement of resistance $R_{41,23}$. Two “perpendicular” resistances which can be used for resistivity measurements are, for instance, $R_{12,34}$ and $R_{23,41}$.

The sheet resistance can be determined from two of these resistances - one measured along a vertical edge, such as $R_{\text{vertical}} = R_{12,34}$, and a corresponding one measured along a horizontal edge, such as $R_{\text{horizontal}} = R_{23,41}$. The actual sheet resistance is related to these resistances by the van der Pauw equation:

$$\exp \left(-\frac{\pi R_{\text{vertical}}}{R_S}\right) + \exp \left(-\frac{\pi R_{\text{horizontal}}}{R_S}\right) = 1$$
For symmetrical samples, e.g. square samples used in this lab work, \( R_{vertical} = R_{horizontal} = R \) and the equation (3) has simple solution:

\[
R_s = \frac{\pi R}{\ln 2}
\]  

(4)

In order to obtain a more precise value for the resistances, four van der Pauw resistances for all four sides of the sample are measured and \( R \) is taken as average of these four resistances.

### 2.2.3. Resistance method

Van der Pauw method is usually applied to doped semiconductors of moderate and low resistivity not exceeding 10 kΩ.cm. Resistivity of highly resistive semiconductors, e.g. undoped intrinsic silicon, can be conveniently determined measuring resistance of a rectangular sample (slab) made of this material. For a sample of length \( l \), width \( w \) and thickness \( t \), its resistance \( R \) is:

\[
R = \rho \frac{l}{wt}
\]  

(5)

Thus the resistivity \( \rho \) can be found as:

\[
\rho = R \frac{wt}{l}
\]  

(6)

The most correct measurements of resistance are performed by four-probe method. Current in the sample is generated applying voltage to the outer contacts on the slab while voltage is measured between the internal contacts. The length \( l \) in the Eq. 5 is the distance between the internal contacts.

The advantage of the four-probe method, as compared with the two-probe method, is the exclusion of resistances of the contacts from the measurements. The contact resistances are usually unknown and, when comparable with the resistance of the sample, they may cause considerable experimental error.

### 2.2.4 “Hot-Probe” method

When a piece of semiconductor is heated non-uniformly, the charge carriers diffuse from hot region in cold one generating this way a voltage (thermo-voltage) between these regions (Fig. 3).

![Fig. 3. Generation of thermo-voltage between hot and cold ends of a semiconductor slab.](image)

Since sign of thermo-voltage corresponds to the sign of the diffusing charge carriers, the measurement of the voltage induced between hot and cold contacts on a piece of semiconductor is a simple way to determine its conductivity type. This measurement known as the "hot-probe" method provides a simple way to distinguish between \( n \)-type and \( p \)-type semiconductors and can be easily demonstrated using a soldering iron and a standard multi-meter. The experiment is
performed by contacting a semiconductor sample with a "hot" probe (tip of heated soldering iron) and a "cold" probe (regular contact). Both probes are wired to a sensitive volt-meter. The hot probe is connected to the positive terminal of the meter, while the cold probe is connected to the negative terminal. The experimental set-up is shown in Fig. 4.

![Fig. 4. Principle of experimental set-up of the "hot-probe" experiment.](image)

2.3. Experimental Equipment
- 2 van der Pauw samples of doped silicon (\textit{n}-type and \textit{p}-type) with holders
- 1 bar sample of intrinsic silicon with holder
- various free standing samples of silicon
- LabView measurement set-up from Lab#1
- DC Power Supply
- Digital Multimeter
- Soldering Iron
- Micrometer

2.4. Procedure
2.4.1. Van der Pauw measurements
1. Assemble the measuring set-up.
2. Measure van der Pauw resistances along all sides of the \textit{n}-type van der Pauw samples for both directions of current.
3. Calculate average van der Pauw resistance and sheet resistivity of the sample using Eq. 4.
4. Measure thickness of the samples using micrometer.
5. Calculate resistivity of the sample using Eq.1.
6. Repeat the measurements on the \textit{p}-type van der Pauw sample.
2.4.2. Resistance method
1. Assemble the measuring set-up.
2. Apply voltage to the outer contacts of one of the intrinsic samples and measure current flowing through the sample.
3. Measure voltage between the internal contacts.
4. Calculate resistance dividing the measured voltage by the measured current.
5. Measure thickness of the sample, its width and the distance (length) between the internal contacts using micrometer or caliper.
6. Calculate resistivity of the sample using Eq. 6.

2.4.3. “Hot-Probe” measurements
1. Connect digital voltmeter to the metal substrate and to the tip the soldering iron.
2. Place one of the samples on the substrate.
3. Switch on soldering iron and wait until it is hot.
4. Touch sample with the hot tip and immediately take reading of the voltmeter. Note the sign of the reading.
5. Repeat the measurements on another free-standing samples.

2.5. Procedure
1. Discuss the processes of measurements and the obtained results.
2. Compare values of resistivities measured by van der Pauw and resistance methods.
3. Using standard values of mobilities of electrons and holes in silicon, calculate concentrations of major charge carriers in the measured samples.
4. Discuss the results of your calculations.
5. Compare the data obtained by the van der Pauw and resistance methods.

2.6. Questions
1. Which of the methods used in this lab work is the most accurate? Why?
2. Why is the four-point measurement of resistance more accurate than the two-point one?
3. Predict the magnitude of mobility in the silicon samples you have measured.
4. How does thermo-voltage depend on concentration of charge carriers and mobility?
Taking Measurements with LabView

**Resistance Method**
1) Use the same setup as Lab#1, except with the decade box set to 100kΩ

2) In LabView, change the “external shunt resistor” to 100kΩ, and min/max set to ±10μA

**Van der Pauw Method**
1) Change the 100kΩ back to 1kΩ, and change the min/max back to ±10mA
2) Set up the circuit as shown below

3) Make sure both channels are set to GS
4) As you can see, current is measured between 1 and 4, and voltage is between 2 and 3, therefore $R_{41,23} = \frac{V}{I}$
5) Rotate the wires to obtain measurements for $R_{12,34}, R_{23,41}, R_{34,12}$ and take the average R
6) Repeat with both *p-type* and *n-type* samples