Experiment Instructions
Transport Properties of Charge Carriers in Semiconductors II
- Hall Effect in the Channel of Field-effect Transistors -

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Introduction and Prerequisites
This experiment is the second part of the lab course series „Transport Properties of Charge Carriers in Semiconductors“. It is an advanced experiment, which requires the successful completion of part one. As an exception, both parts may be booked at once. In this case, the preparation and the report may be combined in one document. Fundamental knowledge in solid state physics (e.g. from the lecture Experimentalphysik VI: Festkörperphysik) is required for the experiment. The following should be known and understood:

- density of states (free particle 1D, 2D and 3D)
- dispersion relation of electrons in semiconductors (band structure, effective mass approximation)
- charge carrier statistics (Fermi-Dirac distribution, Fermi integral, effective density of states)
- p-n junction

1 What is it all about?

In the experiment we investigate a 4H-SiC\textsuperscript{1} MOSFET\textsuperscript{2} by current-voltage characteristics and Hall effect measurements. 4H-SiC is a so called „wide band gap semiconductor“, which is particularly

\textsuperscript{1}4H-SiC: silicon carbide with hexagonal lattice; the stacking sequence of Si-C double layers shows a periodicity of 4.
\textsuperscript{2}MOSFET: metal oxide semiconductor field-effect transistor
suited for power electronic devices. The fabrication of SiC MOSFETs is challenging due to many defects present at the interface between semiconductor and thermally grown oxide. In order to compare various oxidation and post-oxidation techniques for the fabrication and improvement of the interface, the investigation of the density of electrically active defects at the interface is required. To this aim different methods have been developed. A particularly meaningful method is based on the gate voltage-dependent measurement of free charge carrier density in the inversion channel $n_{\text{inv}}(V_G)$ by Hall effect. Through a comparison with simulated ideal MOSFET ($n_{\text{inv}}^{\text{ideal}}(V_G)$), the density of interface traps can be determined. Moreover, this method gives access to the charge carrier mobility in the inversion channel of the device, which is important for the channel resistance and, thus, for the power loss during device operation.

2 Literature

- Theses:
  [ZUE15] M. Zürl, Zulassungsarbeit, Erlangen 2015, chapters 1 to 3 (also available in English)
  [LEH16] J. Lehmeyer, Bachelorarbeit, Erlangen 2016, chapters 2 and 3

- Textbooks on semiconductors, semiconductor devices and measurement methods:
  [SZE07] S.M. Sze, Physics of Semiconductor Devices, John Wiley & Sons, Hoboken 2007 ( chapters 1.4, 1.5.1, 1.5.2, 4, 6.1-6.2.2)
  [SCH06] D.K. Schroder, Semiconductor Material and Device Characterization, John Wiley & Sons, New York 1990 ( chapters 2.5, 4.6, 4.8, 8.6)

- Scientific publications on Hall effect investigations of SiC MOSFETs:

- Semiconductor material properties:
3 Preparation

The preparation should summarize the physical concepts relevant for the experiment as well as the equation necessary for measurement and evaluation. Please avoid detailed derivations and repetitions of basic knowledge from experimental physics lectures (it’s better to motivate equations with one sentence and to cite the related literature). The preparation is a written document with 4 to 6 pages (including text and figures). Address the following items:

- **Basics of semiconductor physics:**
  - Energy levels in the band scheme (Fermi level, conduction band edge and valence band edge, impurity levels)
  - Calculation of the temperature dependence of the Fermi level (chemical potential) in doped semiconductors by numerical solution of the neutrality equation

- **Metal oxide semiconductor field-effect transistors:**
  - Band scheme of the metal oxide semiconductor structure in accumulation, depletion and inversion
  - Schematics and operation of MOSFETs
  - Current-voltage characteristics: output and transfer characteristics
  - Effective mobility and field-effect mobility
  - Relation between gate voltage and surface Fermi potential (including interface traps and fixed oxide charge)
  - Dependence of inversion charge carrier density on surface Fermi potential (charge sheet model)

- **Hall effect measurements:**
  - Hall coefficient, Hall mobility and Hall scattering factor
  - Units of Hall coefficient $R_H$ and sheet resistance $R_S$ of the inversion layer of a MOSFET (2D instead of 3D)
  - Measurement protocol and equations for the calculation of charge carrier density, conductivity and Hall mobility from measurement data ($I$-$V$ characteristics)

In the colloquium, the following questions will be discussed:

- How does the band scheme of a metal oxide semiconductor structure (MOS capacitor) look like in accumulation, depletion and inversion?
- What is a MOSFET and how does it work?
- How do current-voltage characteristics of an ideal and of a real MOSFET look like and why?
- What is the surface Fermi potential $\phi_S$ and how is it related to the charge carrier density $n_{inv}(V_G)$ in the inversion channel?
- How is Hall effect measured on a MOSFET device?
- Which information can you obtain from Hall effect investigations on a MOSFET?
4 Experiment

After successful completion of the colloquium, the experiment can start. At first, you will define and test measurement protocols. Then these measurement protocols are used for automatic measurement of the provided sample. During the measurement, you will do numerical calculations with the help of the tutor. These calculations are needed for the evaluation of the measurement data.

The sample is a 4H-SiC metal oxide semiconductor field-effect transistor (MOSFET), which will be investigated by 3-terminal I-V characteristics as well as Hall effect measurements. Various methods for the characterization of MOSFET performances will be discussed and compared. Further, the density of interface defects will be determined from the measurement of the inversion charge carrier density and the comparison to the simulation of an ideal MOSFET.

4.1 Experimental

1. Install the sample into the cryostat with the help of the tutor.

2. At first, measure the output characteristics for at least 5 different gate voltages. Choose reasonable voltages and do not exceed \( V_G = 30 \text{ V} \)

3. Record at least 3 transfer characteristics for various drain voltages (at least for one characteristic, \( V_D \) should be chosen in the linear regime of the output characteristics). \( V_{G,\text{max}} = 30 \text{ V} \)

4. Define a measurement protocol to measure the conductivity and Hall effect in the channel of the MOSFET sample. What is important with respect to the choice of \( V_D \)? Perform a test measurement with a reasonable gate voltage.

5. Start the program Auto Gatesweep from the menu item Tools and measure conductivity and Hall effect as a function of the gate voltage.
4.2 Numerical calculations

For the determination of the density of interface traps $D_{it}$ from Hall effect measurements, the simulation of an ideal MOSFET without interface traps and fixed oxide charge is required. To this aim, material and device parameters are need. You can find them in the internet (e.g. [IOFFE]) and in the following table:

<table>
<thead>
<tr>
<th>metal</th>
<th>oxide</th>
<th>semiconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>$W_M$ (eV)</td>
<td>material</td>
</tr>
<tr>
<td>poly silicon</td>
<td>4.07</td>
<td>SiO$_2$</td>
</tr>
</tbody>
</table>

In the following, the inversion charge carrier density $n_{\text{inv}}$ as well as the gate voltage $V_G$ will be calculated as a function of the surface Fermi potential $\phi_S$. The procedure is as follows:

1. Choose a reasonable reference value for the energy scale (e.g. $E_V = 0$).
2. Calculate the intrinsic level $E_i$ and the Fermi level $E_F$ in the bulk of the semiconductor (i.e. far away from the interface).
3. Implement the functions $G_1(\phi_S)$, $G_2(\phi_S)$, $Q_{sc}(\phi_S)$ and $Q_{\text{dep}}(\phi_S)$ (cf. [LEH16]).
4. Define the function $n_{\text{inv}}(\phi_S)$ and implement the inverse $\phi_S(n_{\text{inv}}^{\text{mess}})$ by numerically finding the root.
5. Find a relation between the gate voltage $V_{G,\text{ideal}}$ and the surface Fermi potential $\phi_S$ in an ideal transistor without interface defects and fixed oxide charge (cf. [LEH16]).
6. Import your measurement data and calculate the surface Fermi potential $\phi_S$ and the total fixed charge $Q_{\text{tot}} = (V_{G,\text{ideal}} - V_G) \cdot C_\text{ox}$ point-wise. Plot $Q_{\text{tot}}$ vs. $\phi_S$. 

5 Evaluation

The style of the evaluation should be a report like a scientific publication. Start with a brief introduction to the topic. Then describe the experimental details, the experimental results and discuss your findings. Conclude with a summary. Pay attention that all diagrams and figure captions are properly labelled (use empty areas in the diagrams to mention sample data and measurement parameters). Each figure must be referenced in the text. Further, pay attention to complete and correct citation. The page limit is 8 pages including all figures and tables (without preparation, titlepage, table of contents, etc.). Note that not all diagrams have to be included into the report, in particular avoid diagrams which do not give important information. You may also combine measurement results into one diagram. Please do not use too many tables.

1. Plot the output and transfer characteristics. Describe the various regimes. calculate the effective mobility and the field-effect mobility.

2. Plot the Hall mobility as a function of the gate voltage. Add the field-effect mobility and the effective mobility to the same diagram. What do you see? What could be the reason for the differences? What is the approximation used for all mobilities from 3-terminal measurements?

3. Plot the measured and the simulated ideal inversion charge carrier density as a function of the gate voltage. What is the reason for the deviation $\Delta V_G$ at equal charge carrier density? Why is it better to compare measurement and simulation at equal charge carrier density rather than at equal gate voltage?

4. Determine the density of interface traps $D_{it}$ of the MOSFET. Discuss the influence of the density of interface traps on the channel resistance of the MOSFET. Why is the channel resistance of particular importance in power electronic MOSFETs?
6 Appendix

6.1 Description of the measurement program

After the program start you will be asked to create a group folder. All the data will be stored in that folder. The main program Measurement Program will be explained in the following.

Front Panel

Config Measurement
Opens the subprogram to create the measurement protocol. You can create as many steps as you like. It is also possible to load a previously saved measurement protocol.

V_{source}
You can set the drain voltage for the measurements there. If the measurement mode is set to "0.. +Vs/ −Vs.. +Vs", the drain voltage will be swept from 0 V / −V_{source} to +V_{source}.

T averaged
If you start measuring, the temperature will be measured after each step. The averaged temperature is displayed here.

Start Measurement
This button starts a measurement according to the programmed measurement protocol. While measuring, all other buttons are deactivated. You can only start a measurement when a measurement protocol is defined.

Table
The table shows the currently measured values. After each measurement step a new entry appears.

PID controller
In this area you can control the temperature. With Setpoint you can choose a temperature, the program will control the cooling and heating system according to this value. Actual Value shows the current temperature, Output Valve the current valve position. Below there is a button to activate and deactivate the temperature control system. You should start the cool down before the measurements. This is because the temperature control system works much better from lower to higher temperatures. With Reset PID you can reset the integral value of the PID controller and clear the displayed temperature curve.

Menu bar

File
With Export you can save the data of the temperature curve or the measured I-V curves as a text file. With Close you can close the program.

View
In this menu you can display the subprograms PID-Tracing and Data Analysis. PID-Tracing shows the settings and curves of the PID controller. The subprogram Data Analysis lists all measured points. You can start the data analysis by
entering formulas into the input box *Formulas* and creating the corresponding plots. New measurement data will be added automatically. Closing *Data Analysis* does not delete your data, it just hides the window.

**Tools**
With *Tools* 2-terminal and 3-terminal characteristics can be measured. Additionally, you can find the programs for automatic gate and temperature sweeps there.

**Config**
This menu allows you to open the configuration menus for *PID-Controller* or the *Hardware*. 
6.2 Schematic diagram of the experiment
### 6.3 Explanations for the hardware

<table>
<thead>
<tr>
<th>term</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2901A</td>
<td><strong>Source-Measure-Unit</strong>&lt;br&gt;(source drain voltage, measure drain current)</td>
</tr>
<tr>
<td>B2902A</td>
<td><strong>Source-Measure-Unit</strong>&lt;br&gt;(channel 1: voltage measurement low, channel 2: voltage measurement high)</td>
</tr>
<tr>
<td>6430</td>
<td><strong>Source-Measure-Unit</strong>&lt;br&gt;(source gate voltage, measure leakage current)</td>
</tr>
<tr>
<td>34972A</td>
<td><strong>Data Acquisition/Switch Unit</strong>&lt;br&gt;(temperature measurement, relais matrix to switch contacts)</td>
</tr>
<tr>
<td>UNO 2.5, DUO 2.5</td>
<td>vacuum pumps</td>
</tr>
<tr>
<td>ONF4-20</td>
<td>oil mist eliminator</td>
</tr>
<tr>
<td>PSP 1405</td>
<td>programable power supply (cooling system)</td>
</tr>
<tr>
<td>PSP 1803</td>
<td>programable power supply (heating system)</td>
</tr>
<tr>
<td>AVC016SA</td>
<td>valve</td>
</tr>
<tr>
<td>TPR280, TPG261</td>
<td>pressure sensor and evaluation unit</td>
</tr>
<tr>
<td>LV10K</td>
<td>needle valve</td>
</tr>
<tr>
<td>Magnet control unit</td>
<td>control unit for the magnet</td>
</tr>
<tr>
<td>MTN 2800-650</td>
<td>power supply for the magnet</td>
</tr>
</tbody>
</table>