Hall Measurements with MeasureLINK™-MCS Software

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I. Introduction

A basic Hall measurement consists of three steps:

1. Checking the sample contacts to ensure they are ohmic (i.e., linear).
2. Measuring the resistivity. These first two steps are performed at 0 T field.
3. Placing the sample into a known magnetic field and measuring the Hall voltage.

After the completion of these measurements, the derived parameters can be calculated. The FastHall™ station automates the process of entering the required input parameters, collecting the measurement data, and reporting the output results. The steps for completing a standard measurement are shown below.

II. Static Hall Measurement

Scripts for fixed-point Hall measurements are included in the MeasureLINK-MCS™ software. This script completes a Hall measurement at a single field for a van der Pauw sample. To use this script, open the software and follow the steps below.

1. Click **Sequence**.
2. In the Sequence window, click **Measurement**.
3. Click **M91 FastHall™**.
4. Click the desired measurement type to add it.
5. Fill out the fields in each section of the screen.
6. After setting the parameters, click **Start**. The software will tell you when to move the magnet. When complete, the carrier type should be n-type and the mobility about 24000 $cm^2/(V\ s)$.

Preferences

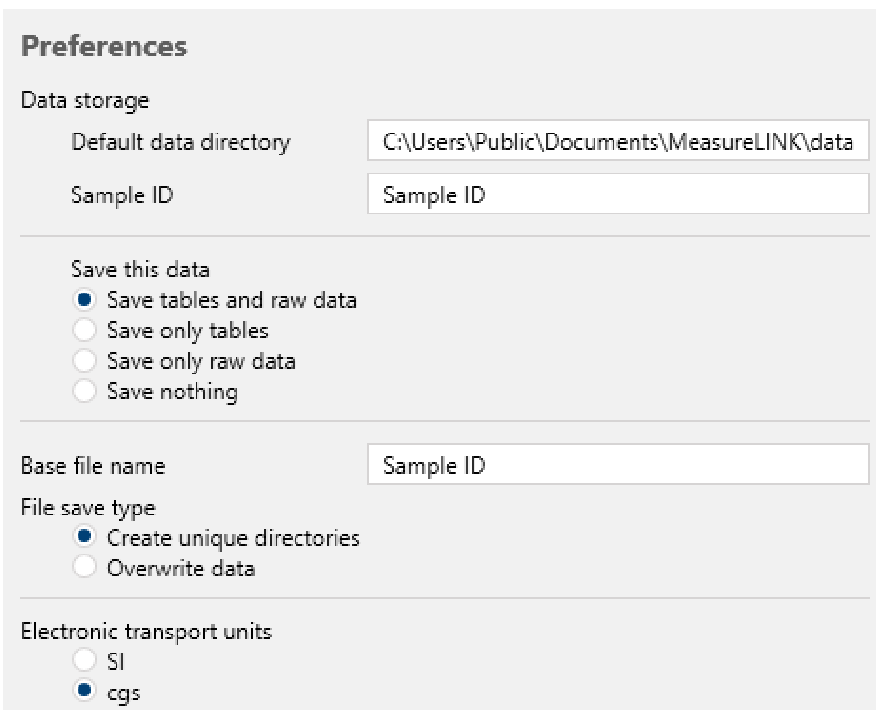

*Figure 1: **Preferences***

Preferences defines where and how data will be stored, and the units for displaying data:

- *Default data directory:* specifies the base directory to store all data for the measurement.
- *Sample ID:* user-specified name for the sample. It is an optional input.
- *Save this data:* there are four choices for saving data:
    - *Save tables and raw data:* saves any table created by the measurement. Tables will have the extension ".csv" and are stored as comma delimited data files. The raw data will have extension ".json." This is the complete record of all data for the measurement. It is a structured JSON data file.
    - *Save only tables:* only the .csv table file will be saved.
    - *Save only raw data:* only the raw data will be saved.
    - *Save nothing:* nothing will be saved.

  NOTE: In addition to the table and raw data files, there is a summary file with the extension ".html." This file is always saved, except when the save nothing choice is selected.
- *Base file name:* the Base file name from which all file names for this measurement will be generated. It defaults to the Sample ID. Changing the Sample ID will change the Base file name, but changing the Base file name will not change the Sample ID.
    - *File save type:* determines how the files are saved.
        - *Create unique directories:* when this option is selected, a new directory (as a sub directory in the Default data directory) is created for each execution of the measurement. The file name is Base file name + "Run #", where # is an integer, to make the directory name unique. The files stored in the directory (".csv", ".json", and ".html") will also have a unique file name using the "Run #".
        - *Overwrite data:* when this is selected, no unique directories of filenames are generated. The example below shows the default directory after 21 runs using Sample ID as the Base file name:

Name	Date modified	Type	Size
Sample ID Run 1	11/4/2019 3:37 PM	File folder	
Sample ID Run 2	11/4/2019 4:27 PM	File folder	
Sample ID Run 3	11/5/2019 10:25 AM	File folder	
Sample ID Run 4	11/5/2019 2:26 PM	File folder	
Sample ID Run 5	11/5/2019 2:45 PM	File folder	
Sample ID Run 6	11/5/2019 3:32 PM	File folder	
Sample ID Run 7	11/5/2019 4:01 PM	File folder	
Sample ID Run 8	11/5/2019 4:06 PM	File folder	
Sample ID Run 9	11/5/2019 4:57 PM	File folder	
Sample ID Run 10	11/6/2019 9:08 AM	File folder	
Sample ID Run 11	11/6/2019 3:33 PM	File folder	
Sample ID Run 12	11/6/2019 6:36 PM	File folder	
Sample ID Run 13	11/11/2019 8:35 AM	File folder	
Sample ID Run 14	11/11/2019 8:38 AM	File folder	
Sample ID Run 15	11/11/2019 8:39 AM	File folder	
Sample ID Run 16	11/11/2019 8:40 AM	File folder	
Sample ID Run 17	11/11/2019 8:41 AM	File folder	
Sample ID Run 18	11/11/2019 8:42 AM	File folder	
Sample ID Run 19	11/11/2019 8:43 AM	File folder	
Sample ID Run 20	11/11/2019 1:21 PM	File folder	
Sample ID Run 21	11/11/2019 1:23 PM	File folder	
Sample ID Run 22	11/11/2019 2:25 PM	File folder	

Figure 2: ***Overwrite data***

The example below shows the detail of the selected file, Sample ID Run 22:

Name	Date modified	Type	Size
12, 12 test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
23, 23 test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
34, 34 test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
41, 41 test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
FastHall Resultstest fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	2 KB
Resistivity Geometry A test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
Resistivity Geometry B test fix field Run 1	1/28/2020 9:52 AM	Microsoft Excel C...	1 KB
test fix field Run 1 ContactCheck	1/28/2020 9:52 AM	JSON File	19 KB
test fix field Run 1 Fast Hall	1/28/2020 9:52 AM	JSON File	20 KB
test fix field Run 1 Resistivity	1/28/2020 9:52 AM	JSON File	36 KB
test fix field Run 1	1/28/2020 9:52 AM	HTML File	13 KB

Figure 3: ***Sample ID Run 22 detail***

- *Electronic transport units:* selects the units for display results. This choice affects resistivity, mobility, carrier concentration, and Hall coefficient.
  - *SI:* for example, m^2/(V s) for mobility.
  - *cgs:* for example, cm^2/(V s) for mobility.

Measurement Setup

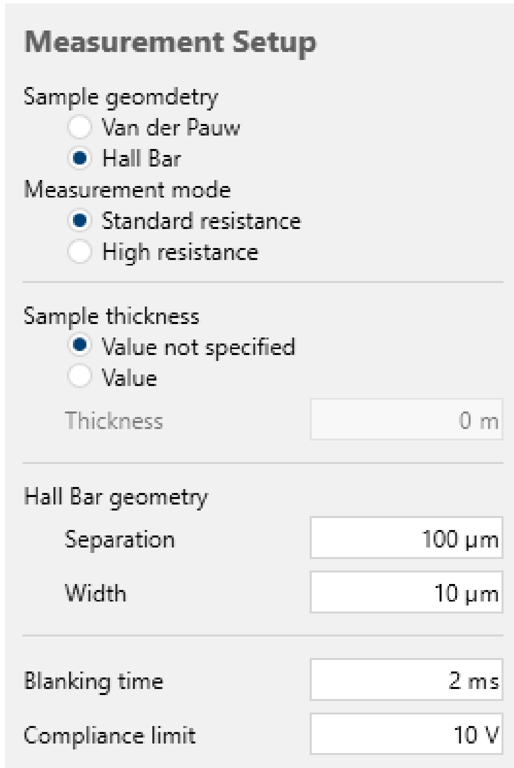

Figure 4: ***Measurement Setup***

Measurement Setup defines the sample parameters of the measurement:

- *Sample geometry:*
    - *Van der Pauw:* selects a van der Pauw sample.
    - *Hall Bar:* selects a Hall bar sample. When Hall Bar is selected, the Hall bar geometry controls in this section are enabled, and the Optimization settings are disabled.
- *Measurement mode:*
    - *Standard resistance:* sources the current and measure voltage, and is supported by every M91.
    - *High resistance:* has the capability to source voltage and measure current, which is generally better for high resistance samples. High resistance mode is only available if the M91 has the high resistance option installed.
- *Sample thickness:* specifies the sample thickness.
    - *Value not specified:* the sample thickness is not specified. The measurement will report sheet values for resistivity, carrier concentration and Hall coefficient.
    - *Value:* enter the thickness in the Thickness field. The units of thickness is meters, but the input has several possible formats.

      As an example, suppose the sample thickness is 100 nanometers. The value can be entered several ways:

      a. 100e-9
      b. 1e-7
      c. 100n
         1. In this case the lowercase n is a multiplier (n for nanometers). The text box will show 100 nanometers in this case.

2. Allowable multipliers are shown in the following table (case sensitive):

Multiplier	Description	Value
t	tera	10^{12}
g	giga	10^{9}
M	mega	10^{6}
k	kilo	10^{3}
m	mill	10^{-3}
u	micro	10^{-6}
n	tera	10^{-9}
p	pico	10^{-12}
a	atto	10^{-15}

Table 1: ***Allowable multipliers***

- *Hall Bar geometry (Hall bar samples only):* there are two required entries for the Hall Bar geometry for resistivity calculations.
    - *Separation:* the separation between the arms.
    - *Width:* the width of the Hall bar.
- *Blanking time:* the blanking time, in seconds. This value will be overwritten if optimization is used.
- *Compliance limit:* the compliance voltage or current. Compliance voltage is only available for standard resistance measurements, and compliance current is only available for high resistance measurements.

Optimization

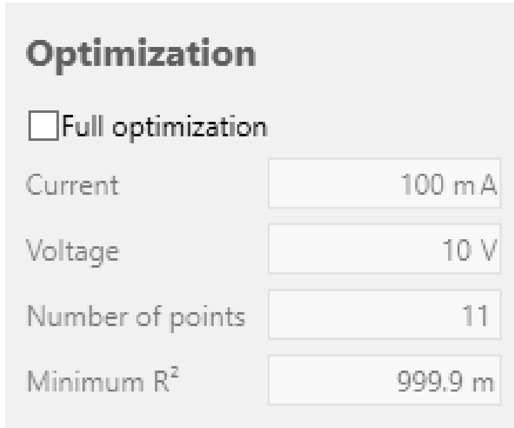

Figure 5: ***Optimization***

Use Optimization mode to determine excitation type and values, and blanking time. Click the Full optimization checkbox to select the optimization measurement. Contact Check, if selected, will deselect.

- *Current:* sets the maximum current to apply to the sample. This is a scaled amp input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *Voltage:* sets the maximum voltage to apply to the sample. This is a scaled volt input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *Number of points:* the number of points in the contact check curve.
- *Minimum R^2:* minimum acceptable correlation coefficient.

When the Optimization method is used, the excitation type, excitation value and blanking time are automatically selected for the measurement.

NOTE: When Hall Bar is selected as the sample type in Measurement Setup, Optimization is disabled. The current firmware does not support optimization for Hall bars.

Contact Check

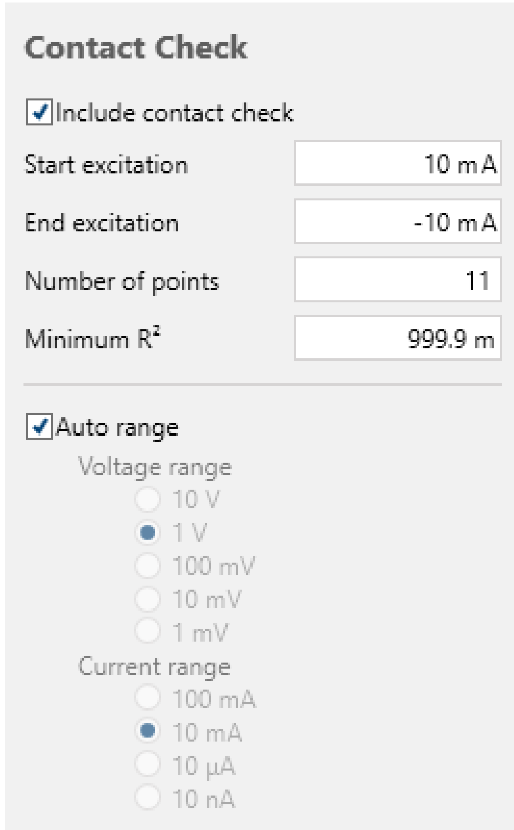

Figure 6: ***Contact Check***

When selected, the measurement will complete a contact check.

For standard resistance measurements:

- *Start excitation:* sets the initial current used for the contact check. This is a scaled amp input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *End excitation:* sets the final current used for the contact check. This is a scaled amp input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.

For high resistance measurements:

- *Start excitation:* sets the initial voltage used for the contact check. This is a scaled volt input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *End excitation:* sets the final voltage used for the contact check. This is a scaled volt input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.

For all measurements:

- *Number of points:* the number of points in the contact check curve.
- *Minimum R^2:* minimum acceptable correlation coefficient.
- *Auto range:* when selected, the measurement range will be determined automatically. If Auto range is not selected, the user must select the measurement range. If the excitation type is current, the range to be selected is the voltage measurement range. If the excitation type is voltage, the range to be selected is the current measurement.

Resistivity

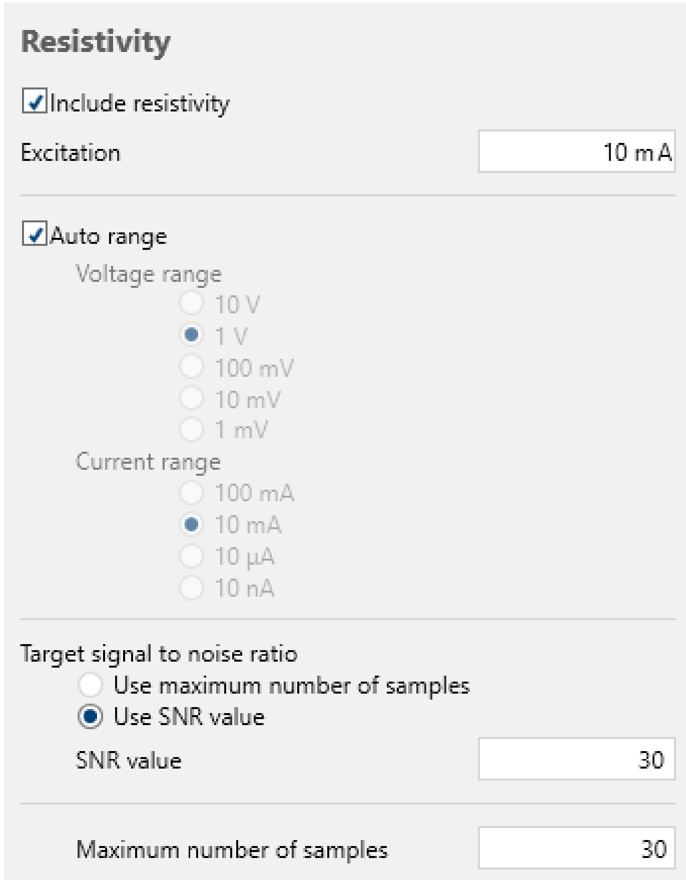

Figure 7: ***Resistivity***

When selected, the measurement will complete a resistivity measurement.

For standard resistance measurements:

- *Excitation:* sets the current used for the resistivity measurement. This is a scaled amp input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.

For high resistance measurements:

- *Excitation:* sets the voltage used for the resistivity measurement. This is a scaled volt input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *Auto range:* when selected, the measurement range will be determined automatically. If Auto range is not selected, the user must specify the measurement range for both current and voltage.
- *Target signal to noise ratio:* specifies the SRN to be obtained, or the maximum number of samples to use:
    - *SNR value:* enter an SNR value.
- *Maximum number of samples:* the number of samples to use. For a value of SNR ratio, the maximum number of samples in the measurement. The measurement will stop when the target SNR is reached, or the number of samples reaches the maximum number of samples.

Hall Measurement

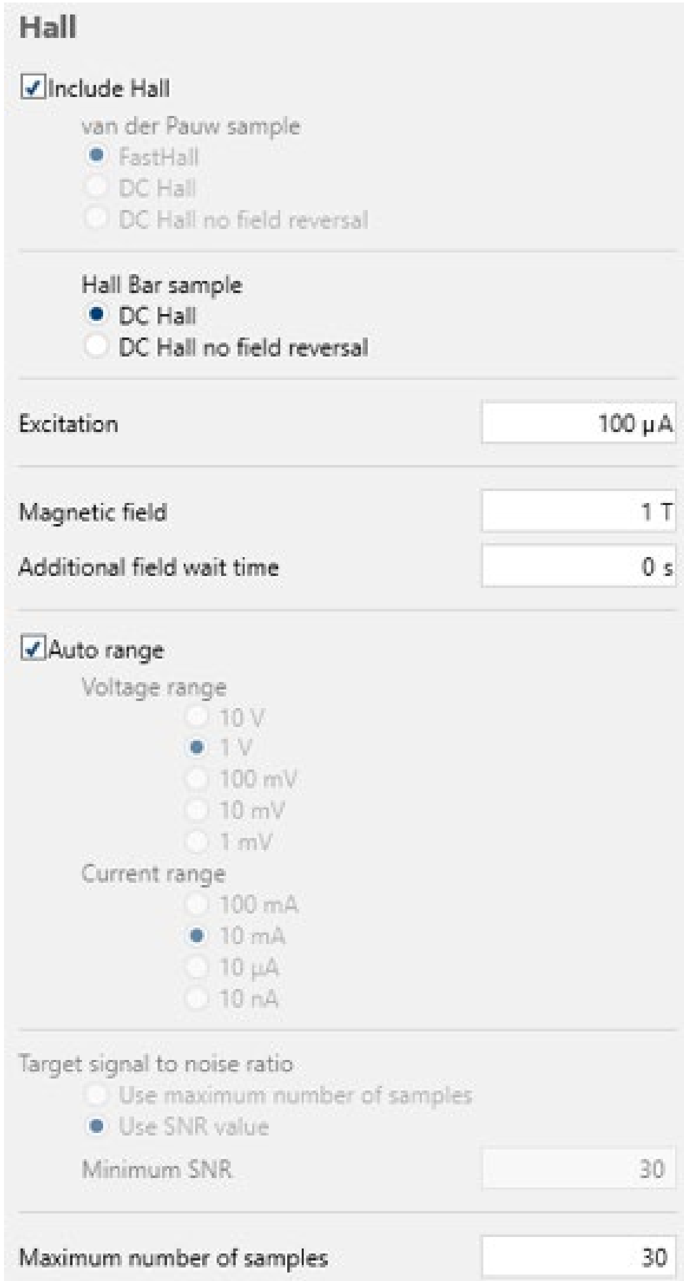

Figure 8: ***Hall***

When selected, the measurement will include a Hall measurement.

Select a method:

- *FastHall:* uses the FastHall™ method.
- *DC Hall:* uses the DC Hall measurement. This will use field reversal.
- *DC Hall no field reversal:* uses DC Hall measurement without field reversal.

NOTE: When Hall Bar is selected as the sample type in Measurement Setup, only the DC Hall and DC Hall no field reversal methods are available.

For standard resistance measurements:

- *Excitation:* sets the current used for the Hall measurement. This is a scaled amp input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.

For high resistance measurements:

- *Excitation:* sets the voltage used for the Hall measurement. This is a scaled volt input. See Sample thickness in the Measurement Setup section for descriptions of scaled input boxes.
- *Magnetic field:* the value of the magnetic field to use in the measurement. Can be positive, negative or zero. Field value is Tesla (T).
- *Additional field wait time:* Sets an additional wait time, in seconds, after the field controller is settled. The default value is 0.
- *Auto range:* when selected, the measurement range will be determined automatically. If Auto range is not selected, the user must specify the measurement range for both current and voltage.
- *Target signal to noise ratio:* specifies the SRN to be obtained, or the maximum number of samples to use:
    - *Minimum SNR:* enter a value to obtain in the Minimum SNR field.
- *Maximum number of samples:* the number of samples to use. For a Default or Value SNR ratio, the maximum number of samples in the measurement. The measurement will stop when the target SNR is reached, or the number of samples reaches the maximum number of samples.

III. Variable Field Hall Measurement

To complete a variable field Hall measurement, open the MeasureLINK-MCS™ software and follow these steps:

1. Click **Sequence**.
2. In the Sequence window, click **Measurement**.
3. Click **M91 FastHall™**.
4. Click **Variable field Hall measurement**.
5. Fill out the fields in each section of the screen, as shown on the following pages.
6. After setting the parameters, click **Start**. The software will tell you when to move the magnet.

Field Loop

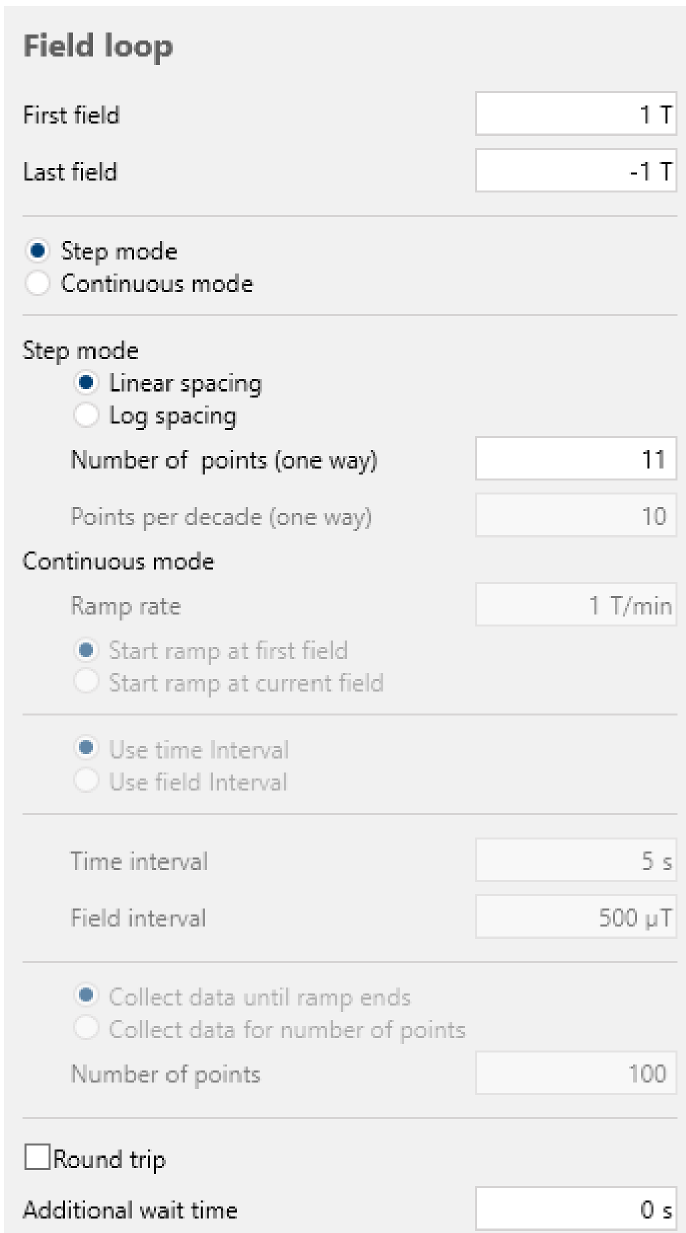

*Figure 9: **Field Loop***

When selected, the measurement will include field loop data:

- *First field*: starting field value for the field swept Hall measurements.
- *Last field*: last field value for the field swept Hall measurements. After measurement execution, the field is returned to 0 T.
- *Step mode:* stabilizes the field at the preset number of steps and waits for the field to settle at each field before completing the Hall measurement. In addition to the Number of points, the user must also specify equally-spaced Linear spacing, or Log spacing (logarithmic spacing).
- *Continuous mode:* starts at the first field and waits for the field to stabilize, then the field ramps to the final field at the user-specified field ramp rate. Hall measurements are taken at fixed intervals, specified to be either fixed time intervals or fixed field intervals. In addition, the continuous mode also supports stopping after a given number of Hall measurements are complete, or continuing until the Last field.
- *Round trip:* directs the software to perform a second field loop with all the settings the same except that the First field and Last field settings are reversed. When this is selected, an Additional wait time can be entered before the return trip begins.

Loop Control

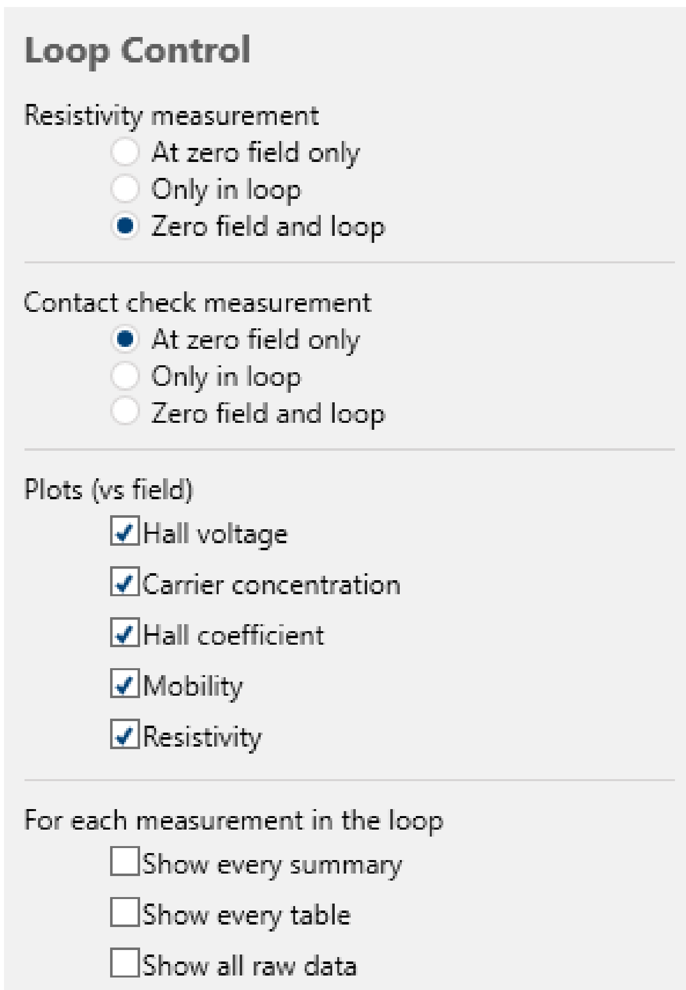

Figure 10: ***Field Loop Control***

- *Resistivity measurement/Contact check measurement:* these settings control when the Resistivity and Contact check measurements are completed during the field sweep:
  - *At zero field only:* completes a resistivity or contact check measurement at 0 T before the sweep begins. The mobility will always be calculated using the zero field resistivity.
  - *Only in loop:* collects a resistivity or contact check measurement and used it each time a Hall measurement is completed.
  - *Zero field and loop:* combines the two previous directives so that the 0 T resistivity or contact check is measured and preserved. Then the resistivity or contact check is collected and used to calculate the Hall analysis at each field.
- *Plots (vs field):* controls the data that is plotted at each field. It is important to remember that the data can be saved separately, in a later step.
- *For each measurement in the loop:* these checkboxes permit the user to control which types (summary, table, data) of output are displayed during the measurement. The data is saved by the Save this data control, even if the output is not displayed.

Preferences

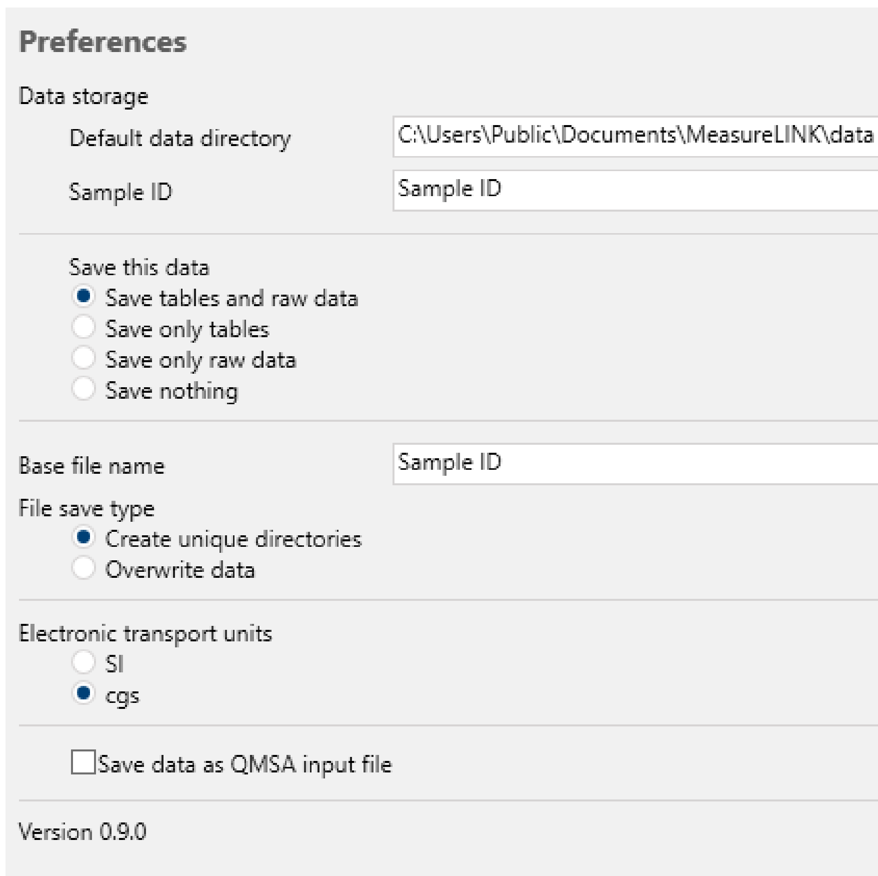

Figure 11: ***Preferences***

Preferences defines where and how data will be stored:

- *Default data directory:* specifies the root folder for all data tables generated during the field sweep.
- *Sample ID:* user-specified name for the sample, used as part of the default file naming convention.
- *Save this data:* there are four choices for saving data. Tables contain relevant summary and calculated data in .csv format.
    - *Save tables and raw data:* saves any table created by the measurement. Tables will have the extension ".csv" and are stored as comma delimited data files. The raw data will have the extension ".json." This is the complete record of all data for the measurement. It is a structured JSON data file. It is useful for drilling down into the constructed measurements for diagnosing problems.
    - *Save only tables:* only the .csv table file will be saved.
    - *Save only raw data:* only the raw data will be saved.
    - *Save nothing:* nothing will be saved.

  NOTE: In addition to the table and raw data files, there is a summary file with the extension ".html." This file is always saved, except when the save nothing choice is selected.
- *Base file name:* the base file name from which all file names for this measurement will be generated. It defaults to the Sample ID, but can be edited to any string appropriate for a file name. Changing the Sample ID will change the Base file name, but changing the Base file name will not change the Sample ID.
    - *File save type:* permits users to specify a new sub-directory under the root folder. This should be created for each Hall analysis, or if the data should continuously overwrite data in the specified root folder.
        - *Create unique directories:* when this option is selected, a new directory (as a sub directory in the Default data directory) is created for each execution of the measurement. The file name is Base file name + field value + either ascending or descending, depending on the direction of the sweep. The files stored in the directory (".csv", ".json" and ".html") will also have a unique file name using the "Run #".
        - *Overwrite data:* when this is selected, no unique directories of filenames are generated. The example below shows the default directory after 21 runs using Sample ID as the Base file name:
- *Electronic Transport Units:* allows the user to specify if SI or cgs units are used in reporting:
    - *SI:* for example, $m^2/(V\ s)$ for mobility.
    - *cgs:* for example, $cm^2/(V\ s)$ for mobility.
- *Save data as QMSA file:* when selected, an additional file is created. This file is in a format that can be used as input for the Lake Shore QMSA program.

Measurement Setup

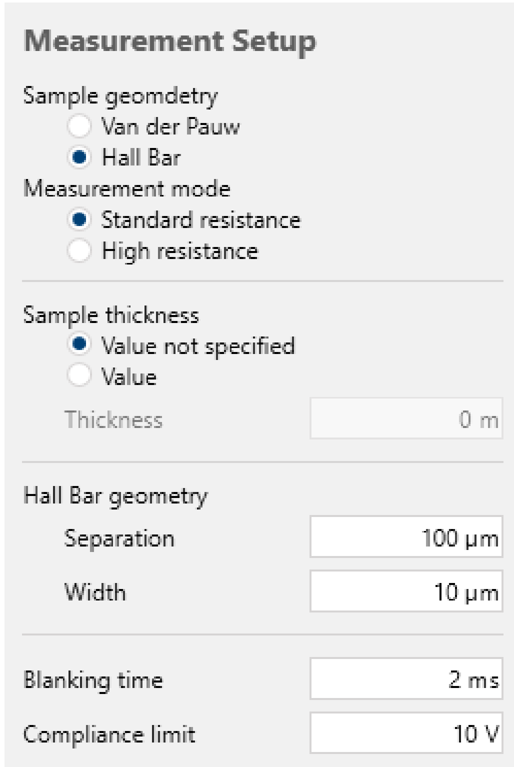

Figure 12: ***Measurement Setup***

Measurement Setup defines the sample parameters of the measurement:

- *Sample geometry:*
  - *Van der Pauw:* selects a van der Pauw sample.
  - *Hall Bar:* selects a Hall bar sample. When Hall Bar is selected, the Hall bar geometry controls in this section are enabled, and the Optimization settings are disabled.
- *Measurement mode:*
  - *Standard resistance:* sources the current and measure voltage, and is supported by every M91.
  - *High resistance:* has the capability to source voltage and measure current, which is generally better for high resistance samples. High resistance mode is only available if the M91 has the high resistance option installed.
- *Sample thickness:* specifies the sample thickness.
  - *Value not specified:* the sample thickness is not specified. The measurement will report sheet values for resistivity, carrier concentration and Hall coefficient.
  - *Value:* enter the thickness in the Thickness field. The scaled meter means that the units of thickness is meters, but the input has several possible formats.
- *Hall Bar geometry (Hall bar samples only):* there are two required entries for the Hall Bar geometry for resistivity calculations.
  - *Separation:* the separation between the arms.
  - *Width:* the width of the Hall bar.
- *Blanking time:* the blanking time, in seconds. This value will be overwritten if optimization is used.
- *Compliance limit:* the compliance voltage or current. Compliance voltage is only available for standard resistance measurements, and compliance current is only available for high resistance measurements.

After all values are entered, you will need to complete the fields for Static Hall Measurement.

NOTE: The settings for Optimization, Contact Check, Resistivity, and Hall are the same as for a Static Hall measurement (section II), except that the Hall field is not set on the Hall Measurement screen. The Hall field is determined from the Loop Control screen.

Optimizing Measurement Time with Variable Field Hall Measurements and QMSA Data

Hall measurements using the FastHall™ method do not require field reversal. However, field reversal should be used with the DC Hall method. This section describes a method to reduce the measurement time of variable field Hall measurements when using DC field Hall methods.

Variable Field Hall Measurements Using the FastHall Method

In this case, the measurement is straight forward. The user specifies the first field for the measurement, the last field for the measurement, and the number of points for linear steps or the number of points per decade for logarithmic steps. Normally the first field and last field would both be positive, but there is no requirement in the scripts for this constraint. For logarithmic sweeps, the first and last field must have the same sign. A new checkbox has been added to the Preferences section of the screen to select QMSA output.

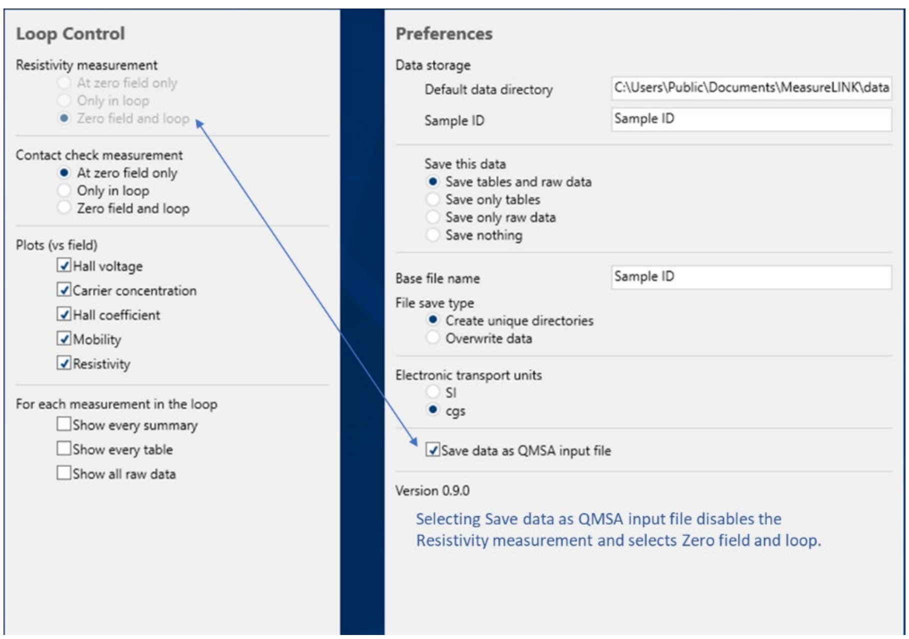

Figure 13: ***Select QMSA output***

QMSA data has several rules, which the script enforces. These include:

- Values are always sheet values, even if a thickness is entered.
- Resistivity must be measured at zero field and within the field loop.
- If cgs units are selected, the field is in Oersted not Tesla.
- A maximum of 30 field points. If more than 30 points are measured, the script randomly picks the excess points to remove from the QMSA file. All data is stored in the .csv files for the measurement.
- The Hall coefficient carries the sign of the carrier type: negative for n-type, positive for p-type.

The file name of the QMSA data file is “Base File Name QMSA data.txt” and is stored in the root data directory of the measurement. This .csv file for the field loop is located in the same directory.

Variable Field Hall Measurements Using the DC Hall Method

Assuming the QMSA data is required, the resistivity must also be measured at field. For example, with a simple three-field variable field Hall measurement, label the fields f_1, f_2, and f_3. If the DC Hall method with field reversal is used in the M91 measurement controller, the following sequence is used:

1. Go to field f_1.
2. Measure resistivity at field.
3. Start DC Hall:
    a. Measure positive field.
    b. Go to $-f_1$.
    c. Measure negative field.
    d. Return field reversed data.
4. This sequence is repeated for fields f_2 and f_3.

NOTE: In this method, there are three excursions (one for each field) from positive field to negative field.

The Time Optimization checkbox in the Hall setup allows a different mode (see Figure 14). This mode is only available when QMSA output is selected and DC Hall is selected. In this example, assume f_1 is greater the f_3.

1. In the Hall section of the screen, click DC Hall no field reversal.
2. Field is swept to f_1.
3. Resistivity is measured.
4. DC Hall no field reversal is measured.
   Results: These results are stored in measurement result (and table) positive field results.
5. Repeat steps 2, 3 and 4 for fields f_2 and f_3, completing the positive field results.
6. Field is swept to $-f_3$.
7. Resistivity is measured.
8. DC Hall no field reversal is measured.
   Results:
   - These results are stored in measurement result (and table) negative field results.
   - The results at $-f_3$ are matched with the results at f_3 and the field reversed results are calculated. These are stored in measurement results (and table) field reversed results.

   NOTE: The field reversed calculations are done in the script not in the M91.
9. Repeat steps 6, 7, and 8 for fields $-f_2$ and $-f_1$.
10. QMSA data is generated from the field reversed measurement.
    NOTE: This method is like the method used in the Lake Shore Model 7700 and the 8400 Series HMS, and the field is swept only once from f_1 to $-f_1$.

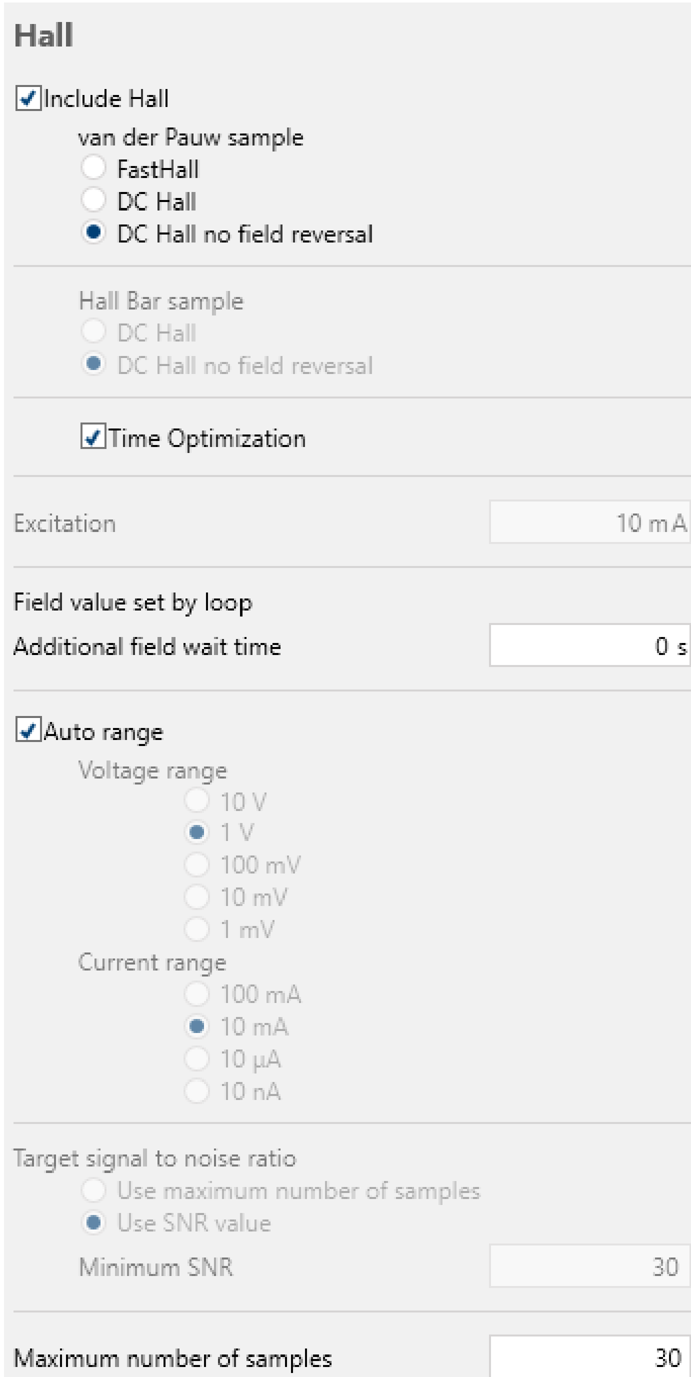

Figure 14: ***Time Optimization***

The tables and plots for this method are shown below.
NOTE: This is data on the standard InAs sample measured on the EMP-4.

Positive field results

Field [T]	Hall Voltage (B+) [V]	Sheet Resistivity (B+) [ohm/□]	Sheet Hall Coefficient (B+)[cm^2/C]	Sheet Carrier Concentration (B+)[1/cm^2]	CarrierType	Mobility(B+) [cm^2
255.000E-3	-8.90801E-3	151.353E-3	-3.49546E3	1.78561E15	N	23.1787E3
227.500E-3	-7.93876E-3	151.244E-3	-3.49166E3	1.78755E15	N	23.1535E3
200.000E-3	-6.97301E-3	151.152E-3	-3.48861E3	1.78911E15	N	23.1332E3
172.500E-3	-6.00721E-3	151.062E-3	-3.48455E3	1.79120E15	N	23.1063E3
145.000E-3	-5.04600E-3	150.983E-3	-3.48205E3	1.79248E15	N	23.0898E3
117.500E-3	-4.08489E-3	150.913E-3	-3.47857E3	1.79427E15	N	23.0667E3
90.0000E-3	-3.12559E-3	150.860E-3	-3.47493E3	1.79615E15	N	23.0426E3
62.5000E-3	-2.16827E-3	150.826E-3	-3.47130E3	1.79803E15	N	23.0185E3
35.0000E-3	-1.21019E-3	150.797E-3	-3.45974E3	1.80404E15	N	22.9418E3
7.50000E-3	-253.117E-6	150.786E-3	-3.37686E3	1.84831E15	N	22.3923E3

Negative field results

Field [T]	Hall Voltage (B-) [V]	Sheet Resistivity (B-) [ohm/□]	Sheet Hall Coefficient (B-)[cm^2/C]	Sheet Carrier Concentration (B-)[1/cm^2]	CarrierType	Mobility(B-) [cm^2/(
-7.50000E-3	268.406E-6	150.782E-3	-3.58085E3	1.74303E15	N	23.7449E3
-35.0000E-3	1.22459E-3	150.797E-3	-3.50084E3	1.78286E15	N	23.2143E3
-62.5000E-3	2.18215E-3	150.821E-3	-3.49345E3	1.78663E15	N	23.1653E3
-90.0000E-3	3.13974E-3	150.853E-3	-3.49057E3	1.78811E15	N	23.1463E3
-117.500E-3	4.09853E-3	150.907E-3	-3.49010E3	1.78835E15	N	23.1432E3
-145.000E-3	5.05970E-3	150.969E-3	-3.49146E3	1.78765E15	N	23.1522E3
-172.500E-3	6.02161E-3	151.050E-3	-3.49278E3	1.78697E15	N	23.1609E3
-200.000E-3	6.98575E-3	151.137E-3	-3.49486E3	1.78591E15	N	23.1747E3
-227.500E-3	7.95210E-3	151.233E-3	-3.49743E3	1.78460E15	N	23.1918E3
-255.000E-3	8.92112E-3	151.340E-3	-3.50045E3	1.78306E15	N	23.2118E3
-282.500E-3	9.89124E-3	151.453E-3	-3.50330E3	1.78161E15	N	23.2307E3

Field reversed results

Field [T]	Hall Voltage (field reversal) [V]	Sheet Resistivity (field reversal) [ohm/□]	Sheet Hall Coefficient (field reversal)[cm^2/C]	Sheet Carrier Concentration (field reversal)[
7.50000E-3	-260.762E-6	150.784E-3	-3.47682E3	1.79518E15
35.0000E-3	-1.21739E-3	150.797E-3	-3.47826E3	1.79443E15
62.5000E-3	-2.17521E-3	150.823E-3	-3.48033E3	1.79336E15
90.0000E-3	-3.13266E-3	150.856E-3	-3.48074E3	1.79316E15
117.500E-3	-4.09171E-3	150.910E-3	-3.48230E3	1.79235E15
145.000E-3	-5.05285E-3	150.976E-3	-3.48472E3	1.79111E15
172.500E-3	-6.01441E-3	151.056E-3	-3.48662E3	1.79013E15
200.000E-3	-6.97938E-3	151.144E-3	-3.48969E3	1.78856E15
227.500E-3	-7.94543E-3	151.238E-3	-3.49250E3	1.78712E15
255.000E-3	-8.91456E-3	151.346E-3	-3.49591E3	1.78538E15
282.500E-3	-9.88602E-3	151.459E-3	-3.49948E3	1.78355E15

Field Loop Table | Sheet Resistivity Chart | Sheet Hall Coefficient Chart | Sheet Carrier Concentration Chart | Mobility Chart | Hall Voltage Chart

Figure 15: ***DC Hall method results***

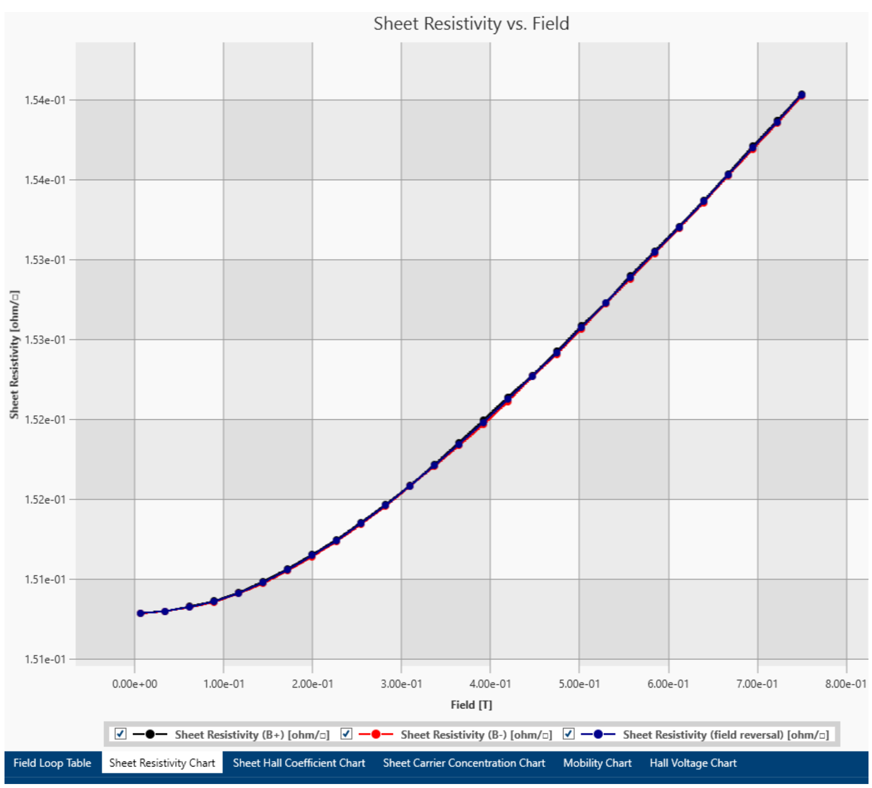

Figure 16: ***Resistivity plot***

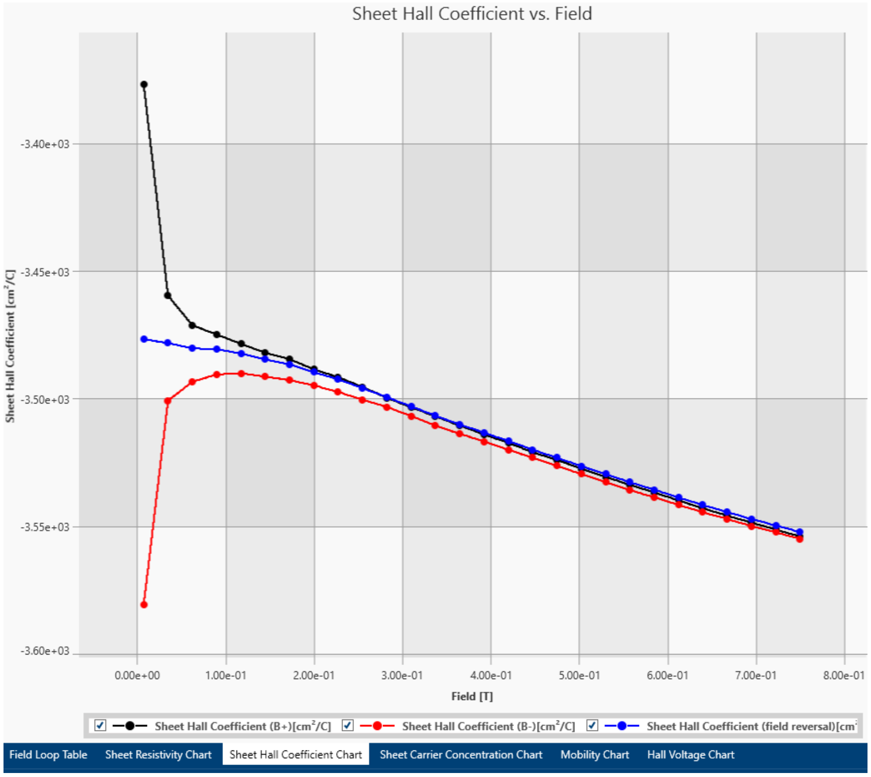

Figure 17: ***Hall coefficient (note values as negative)***

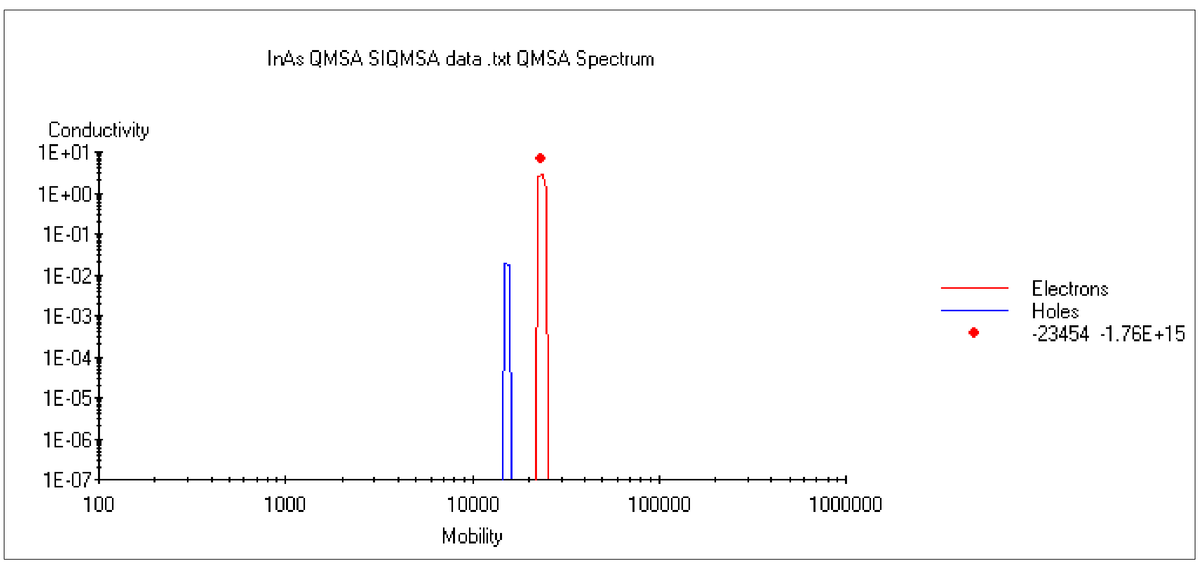

Figure 18: ***QMSA spectrum data***

NOTE: Since the resistivity and Hall coefficient are not constant with field, expect more than one carrier.

In this spectrum plot, the red peak is the electron peak with mobility 23454 $cm^2/(V\ s)$ and sheet carrier concentration of 1.76 10^{15} 1/cm^2. There is a normal InAs result. There is also a small hole carrier with mobility 18400 $cm^2/(V\ s)$ and sheet carrier concertation of 1.35 10^{13} 1/cm^2 . This gives the slight field dependency to the resistivity and Hall coefficient. The resistivity and Hall coefficient change by 2% over the field sweep. The conductivity of the hole is 0.6% of the conductivity of the electron.

IV. Variable Temperature Hall Measurement

To complete a variable temperature Hall measurement, open the MeasureLINK-MCS™ software and follow these steps:

1. Click **Sequence**.
2. In the Sequence window, click **Measurement**.
3. Click **M91 FastHall™**.
4. Click **Variable temperature Hall measurement**.
5. Fill out the fields in each section of the screen, as shown on the following pages.
6. After setting the parameters, click **Start**. The software will tell you when to move the magnet.

Temperature Loop

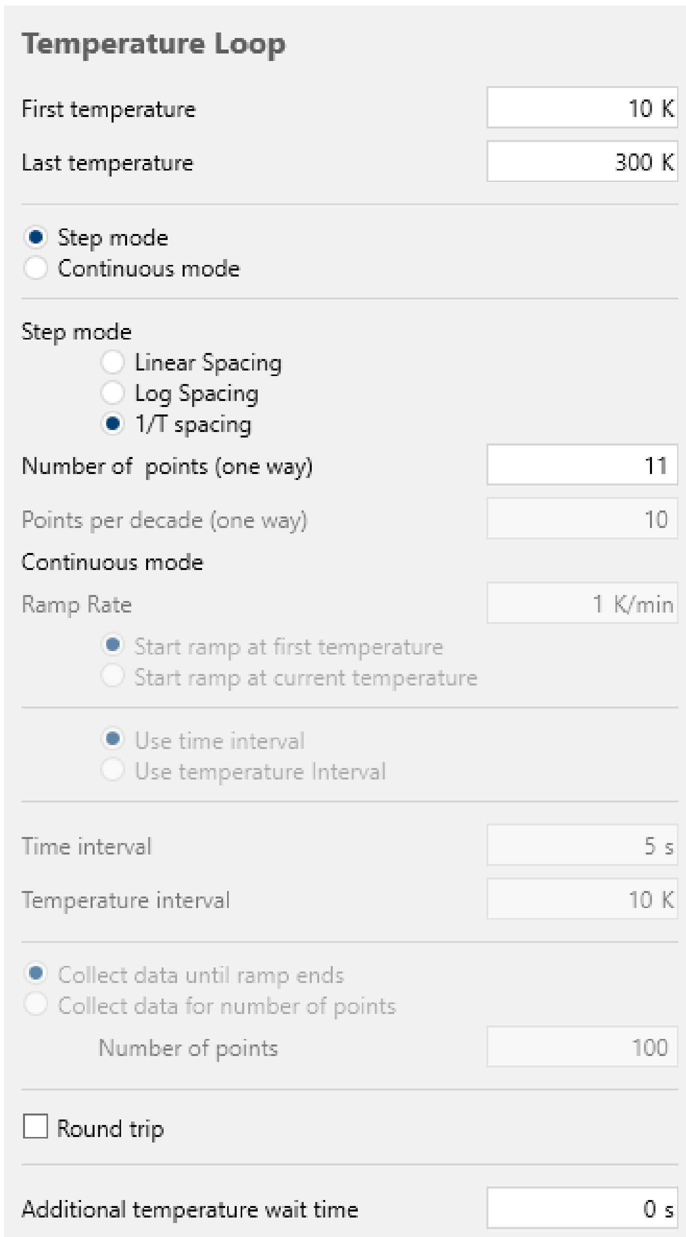

*Figure 19: **Temperature Loop***

When selected, the measurement will include temperature loop data:

- *First temperature*: starting temperature for the measurements.
- *Last temperature*: last temperature for the measurements. After measurement execution, the field is returned to 0 T.
- *Step mode:* stabilizes the temperature at the preset number of steps and waits for the temperature to settle at each step before completing the Hall measurement. In addition to the Number of points, the user must also specify equally-spaced Linear Spacing, or Log Spacing (logarithmic spacing), or 1/T spacing.
- *Continuous mode:* starts at the first temperature and waits for the temperature to stabilize, then the temperature ramps to the final temperature at the user-specified ramp rate. Hall measurements are taken at fixed intervals, specified to be either fixed time intervals or fixed temperature intervals. In addition, the continuous mode also supports stopping after a given number of Hall measurements are complete, or continuing until the Last temperature.
- *Round trip:* directs the software to perform a second temperature loop with all the settings the same except that the First temperature and Last temperature settings are reversed. When this is selected, an Additional temperature wait time can be entered before the return trip begins.

Loop Control

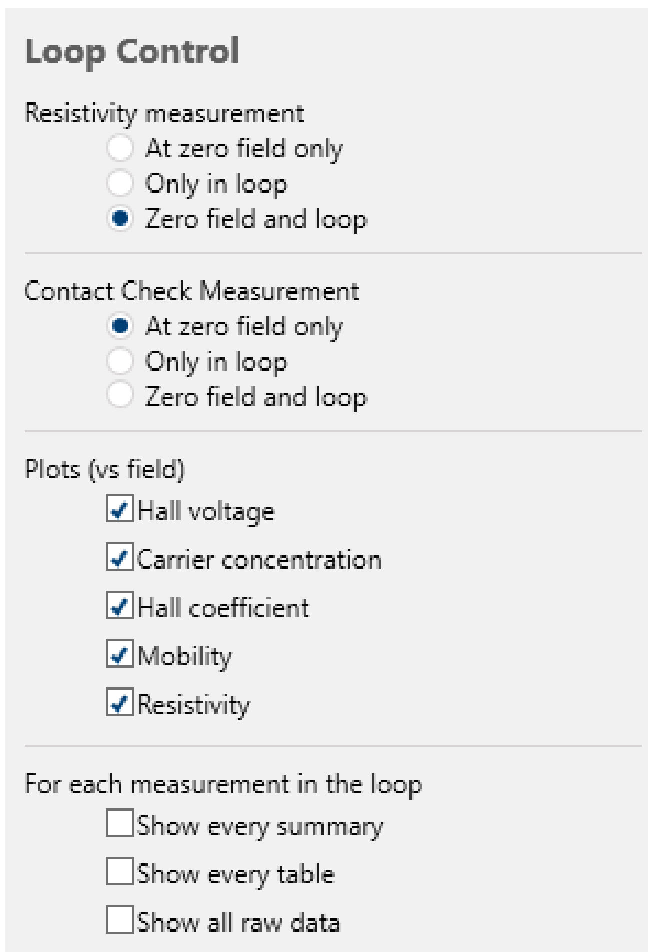

Figure 20: ***Temperature Loop Control***

- *Resistivity Measurement/Contact Check Measurement:* these settings control when the Resistivity and Contact Check measurements are completed during the field sweep:
    - *At zero field only:* completes a resistivity or contact check measurement at 0 T before the sweep begins. The mobility will always be calculated using the zero field resistivity.
    - *Only in loop:* collects a resistivity or contact check measurement and used it each time a Hall measurement is completed.
    - *Zero field and loop:* combines the two previous directives so that the 0 T resistivity or contact check is measured and preserved. Then the resistivity or contact check is collected and used to calculate the Hall analysis at each field.
- *Plots (vs field):* controls the data that is plotted at each field. It is important to remember that the data can be saved separately, in a later step.
- *For each measurement in the loop:* these checkboxes permit the user to control which types (summary, table, data) of output are displayed during the measurement. The data is saved by the Save this data control, even if the output is not displayed.

Preferences

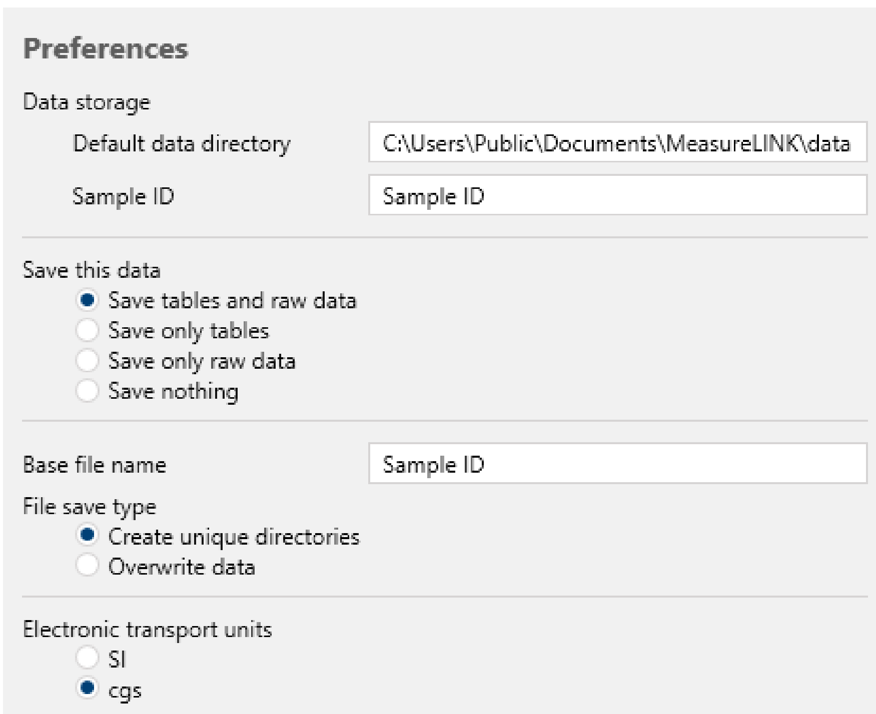

Figure 21: ***Preferences***

Preferences defines where and how data will be stored:

- *Default data directory:* specifies the root folder for all data tables generated during the temperature measurement.
- *Sample ID:* user-specified name for the sample, used as part of the default file naming convention.
- *Save this data:* there are four choices for saving data. Tables contain relevant summary and calculated data in .csv format.
    - *Save tables and raw data:* saves any table created by the measurement. Tables will have the extension ".csv" and are stored as comma delimited data files. The raw data will have the extension ".json." This is the complete record of all data for the measurement. It is a structured

JSON data file. It is useful for drilling down into the constructed measurements for diagnosing problems.
    - *Save only tables:* only the .csv table file will be saved.
    - *Save only raw data:* only the raw data will be saved.
    - *Save nothing:* nothing will be saved.

NOTE: In addition to the table and raw data files, there is a summary file with the extension ".html." This file is always saved, except when the save nothing choice is selected.

- *Base file name:* the base file name from which all file names for this measurement will be generated. It defaults to the Sample ID, but can be edited to any string appropriate for a file name. Changing the Sample ID will change the Base file name, but changing the Base file name will not change the Sample ID.
    - *File save type:* permits users to specify a new sub-directory under the root folder. This should be created for each Hall analysis, or if the data should continuously overwrite data in the specified root folder.
        - *Create unique directories:* when this option is selected, a new directory (as a sub directory in the Default data directory) is created for each execution of the measurement. The file name is Base file name + temperature + either ascending or descending, to make the directory name unique. The files stored in the directory (".csv", ".json" and ".html") will also have a unique file name using the "Run #". The file name is Base file name + "Run #", where # is an integer, to make the directory name unique.
        - *Overwrite data:* when this is selected, no unique directories of filenames are generated. The example below shows the default directory after 21 runs using Sample ID as the base file name:
- *Electronic transport units:* allows the user to specify if SI or cgs units are used in reporting:
    - *SI:* for example, $m^2/(V\ s)$ for mobility.
    - *cgs:* for example, $cm^2/(V\ s)$ for mobility.

Measurement Setup

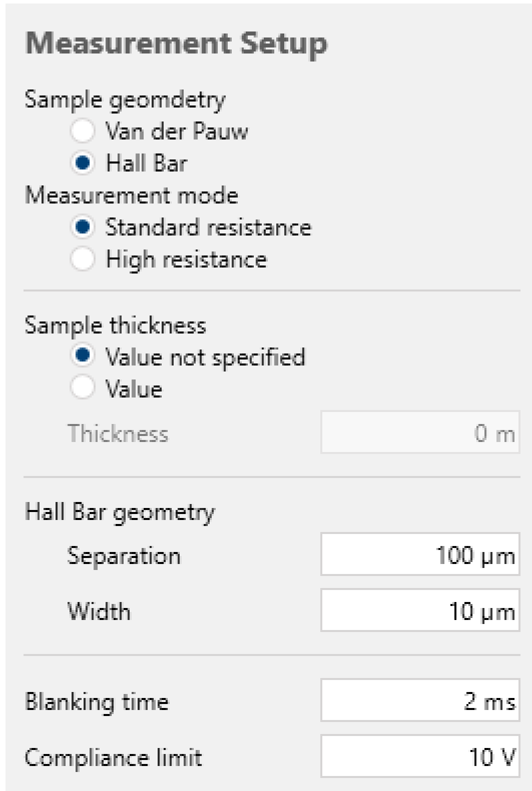

Figure 22: ***Measurement Setup***

Measurement Setup defines the sample parameters of the measurement:

- *Sample geometry:*
  - *Van der Pauw:* selects a van der Pauw sample.
  - *Hall Bar:* selects a Hall bar sample. When Hall Bar is selected, the Hall bar geometry controls in this section are enabled, and the Optimization settings are disabled.
- *Measurement mode:*
  - *Standard resistance:* sources the current and measure voltage, and is supported by every M91.
  - *High resistance:* has the capability to source voltage and measure current, which is generally better for high resistance samples. High resistance mode is only available if the M91 has the high resistance option installed.
- *Sample thickness:* specifies the sample thickness.
  - *Value not specified:* the sample thickness is not specified. The measurement will report sheet values for resistivity, carrier concentration and Hall coefficient.
  - *Value:* enter the thickness in the Thickness field. The scaled meter means that the units of thickness is meters, but the input has several possible formats.
- *Hall Bar geometry (Hall bar samples only):* there are two required entries for the Hall Bar geometry for resistivity calculations.
  - *Separation:* the separation between the arms.
  - *Width:* the width of the Hall bar.
- *Blanking time:* the blanking time, in seconds. This value will be overwritten if optimization is used.
- *Compliance limit:* the compliance voltage or current. Compliance voltage is only available for standard resistance measurements, and compliance current is only available for high resistance measurements.

After all values are entered, you will need to complete the fields for Static Hall Measurement.

NOTE: The settings for Optimization, Contact Check, Resistivity, and Hall are the same as for a Static Hall measurement (section II), except that the Hall field is not set on the Hall Measurement screen. The Hall field is determined from the Loop Control screen.

V. Service

The Lake Shore Service Department is staffed Monday through Friday between the hours of 8:00 a.m. and 5:00 p.m. EST, excluding holidays and company shut down days.

Contact Lake Shore Service through any of the means listed below. However, the most direct and efficient means of contacting is to complete the online service request form at http://www.lakeshore.com/Service/. Provide a detailed description of the problem and the required contact information. You will receive a response within 24 hours or the next business day in the event of weekends or holidays.

If you wish to contact Service or Sales by mail or telephone, use the following:

Mailing address	Lake Shore Cryotronics Instrument Service Department 575 McCorkle Blvd. Westerville, Ohio USA 43082-8888	
E-mail address	sales@lakeshore.com support@lakeshore.com	Sales Instrument Service
Telephone	614-891-2244 614-891-2243 option 6	Sales Instrument Service
Fax	614-818-1600 614-818-1609	Sales Instrument Service
Web service request	http://www.lakeshore.com/Service/	Instrument Service