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# Precision of single-engage micro Hall effect measurements

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## Abstract

Recently a novel microscale Hall effect measurement technique has been developed to extract sheet resistance ($R_S$), Hall sheet carrier density ($N_{HS}$) and Hall mobility ($\mu_H$) from collinear micro 4-point probe measurements in the vicinity of an insulating boundary [1]. The technique measures in less than a minute directly the local transport properties, which enables in-line production monitoring on scribe line test pads [2]. To increase measurement speed and reliability, a method in which 4-point measurements are performed using two different electrode pitches has been developed [3]. In this study we calculate the measurement error on $R_S$, $N_{HS}$ and $\mu_H$ resulting from electrode position errors, probe placement, sample size and Hall signal magnitude. We show the relationship between measurement precision and electrode pitch, which is important when down-scaling the micro 4-point probe to fit smaller test pads. The study is based on Monte Carlo simulations.

## 1. Introduction

Resistance measurements using micro four-point probes (M4PP) [4] is a well-established technique used to monitor the sheet resistance of semiconductor surfaces [5, 6, 7]. Within the last decade the use of M4PP metrology has broadened from development and process monitoring for tunnelling spin valves [8] to characterization of shallow semiconductor junctions [9]. Due to the low sample preparation requirements the technique is readily applied to blanket wafers early in the processing flow, providing valuable high resolution information about processing uniformity [10]. With the introduction of micro fabricated M4PP it is now possible to monitor wafers after lithographic patterning if a suitable measurement pad, not much larger than the probe, is available [11].

It has been demonstrated that a collinear M4PP can be used to perform Hall effect measurements on ultra-shallow junctions [1] when a magnetic flux density $B$ normal to the sample is applied. As described below similar Hall effect measurements can be made using a collinear micro 7-point probe (M7PP) [3]. This study focuses on the precision of single engage M7PP measurements using Monte Carlo simulations to investigate the impact of position errors, Hall signal magnitude and sample size.

## 2. Micro Hall effect measurement principle

The resistance measured with a collinear M4PP is significantly affected by edge effects when placed near a boundary. As demonstrated by Thorsteinsson et al. [11] correction free dual configuration sheet resistance measurements can be made on small test pads if the probe is placed in a mirror plane of the pad. However, for Hall measurements the probe must be placed in the vicinity of a border since that is where the Hall signal emerges. Thus, the edge effects that are normally unwanted are here a necessary element. To perform an accurate measurement the exact probe position must be determined. This is done either by using a M4PP to make two measurements at different distances to the boundary [2, 12, 13], or by using a multi-point probe to measure at a single distance from the edge [3], see Figure 1. Using the latter approach, electrode configurations with different pitches are thus placed at the same absolute distances to the edge.

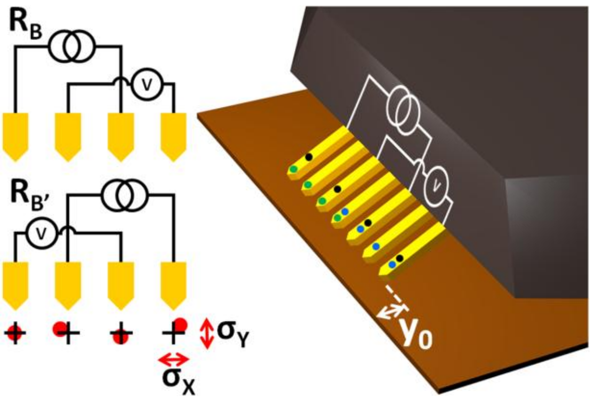


Figure 1: M7PP for single engage Hall measurements near the edge of a rectangular pad. Black dots indicate the 2$s$ pin set (pins 1, 3, 5, 7) while the green and blue dots indicate two 1$s$ pin sets (pins 1-4 and 4-7). $\sigma_X$ and $\sigma_Y$ are random pin position errors realized in each probe engage.

The apparent sheet resistance increases when the probe is moved closer to the edge, and is exactly 2×$R_S$ at the edge of a semi-infinite sample [1]. The dual configuration technique [14] is used to accurately measure the apparent sheet resistances and the ratio of

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measurements performed at different relative distances is used to precisely determine how far the probe is placed from the edge. The Hall signal, which is proportional to the resistance difference $\Delta R_{BB'}$ between $R_B$ and $R_{B'}$ measurements, see Figure 1, is also strongly dependent on the distance to the edge. Thus, the measurements yield two independent ways to determine the distance to the edge: either based on the resistance signal or the Hall signal. In this study the two methods are weighted in accordance with a maximum-likelihood estimation principle. The weights are based on simulations of the mobility variance within the applicable $\mu_H \times B$ range, using a resistance signal-to-noise ratio (SNR) of 3000 and a standard deviation on normally distributed pin position errors with standard deviations $\sigma_X = \sigma_Y = 0.02s$ (see Figure 1), where $s$ is the probe pitch. The SNR used is conservatively chosen from the low end of the range found on a CAPRES M300 tool, and is characteristic when measuring on a difficult sample. Measurements on an easy sample typically have SNR ten times larger. The pin position errors are empirically determined [15] from measurements on an ensemble of semi-conducting samples using a CAPRES microRSP-M150 tool and an $s$ = 10 µm M7PP.

## 3. Measurement errors

The main sources of error in micro Hall effect measurements are: pin position placement errors and noise in the electrical measurement of resistance. Furthermore, as the size of the sample is reduced its geometry will amplify the errors induced by pin position errors.

### *A. Pin position errors*

Pin position errors are defined as displacements of the contact points away from the ideal equidistant positions. They can be divided into two spatial components according to Figure 1: in-line ($\sigma_X$) and off-line ($\sigma_Y$). Furthermore, the errors may be static during an engage i.e. constant throughout a measurement consisting of multiple four-point configurations, but different at each measurement location involving a new engage. Position errors can also be dynamic, meaning the pin positions change between the configurations of a measurement in a single engage. Dynamic position errors are typically not observed in M4PP measurements on semiconductors; the initially established contacts generally last throughout the engage. For this reason dynamic pin offsets are not included in this study.

Using an M7PP the impact of in-line position errors is inherently reduced if the small pitch sub-probes used (pin sets 1-4 and 4-7) exactly covers the pins used for the large pitch sub-probe (pin set 1, 3, 5, 7), see Figure 1. If for example the leftmost pin is displaced slightly away from the others it would equally increase the effective pitch of both the large pitch sub-probe and the mean of the two small pitch sub-probes. Thus the pitch ratio $2s/s$ is maintained. If a pin is slightly closer to the boundary than the others this constitutes an off-line error. To first order the pin offset is equivalent to moving all probes a smaller distance closer to the boundary. Again this maintains the ratio of the measurements and thus the final measurement accuracy.

Further details of position error suppression are described in [3, 16].

### *B. Electrical noise*

The electrical noise appears as a random fluctuation in the measured resistance of each configuration in a measurement. Since the Hall signal is proportional to the resistance difference $\Delta R_{BB'}$, the electrical SNR has the largest impact on the measurement precision of the Hall signal. This reduces the precision of $N_{HS}$ and $\mu_H$ at low mobility values, while it has less of an impact on $R_S$ because it is does not rely on the Hall signal. To improve the precision of the resistance difference, multiple four-point resistance configurations are measured. These resistance values are averaged after a median filtering has removed erratic measurements.

## 4. Monte Carlo simulations

A Monte Carlo approach is readily applied to study the impact of noise on the measurement precision. The simulated measurements are based on the theory described by Petersen et al. [1]. We have implemented the Monte Carlo simulation environment as a script in Matlab. All simulated measurements consist of 3×25 electrode configurations using the three sub-probe pin sets indicated in Figure 1. Only static pin position errors are considered, meaning the pin errors are the same on the 75 configurations of each iteration, but different between each iteration. We have assumed in-line and off-line pin position errors of equal amplitude probability density (standard deviations $\sigma_X = \sigma_Y$) and normally distributed. The electrical noise is individual to each of the 75 configurations and applied as a normally distributed error of magnitude 1/SNR to the simulated resistance.

To obtain statistically significant results of the simulations we have used 4000 iterations to generate each data point in the plots below. The data analysis of simulated measurements is performed using a Matlab script provided by CAPRES A/S; the script is similar to that used in their M300 product line.

## 5. Results

To illustrate where the probe should be placed to obtain the best precision we have simulated the relative standard deviation of the measured parameters for measurements at different distances from the edge of a semi-infinite sample, see Figure 2. While $R_S$ and

$N_{HS}$ are best determined at positions as close as possible to the boundary, $\mu_H$ precision is almost constant up to a few fractions of a pitch from the edge.

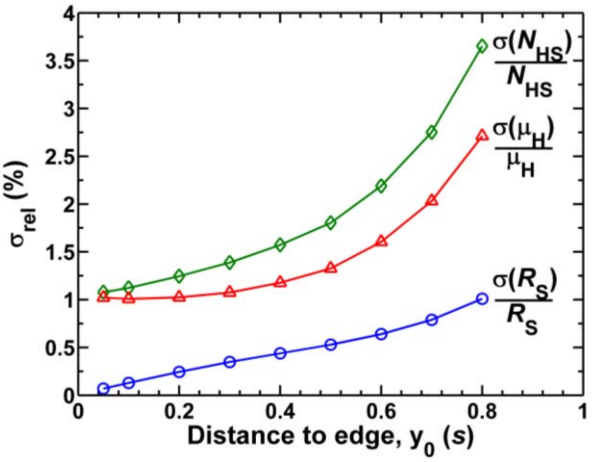


Figure 2: Relative standard deviation vs. distance to the insulating boundary in units of probe pitches. The sample is semi-infinite, pin position error standard deviations $\sigma_X = \sigma_Y = 0.02s$, SNR = 3000, $\mu_H \times B = 0.01$.

The impact of pin position errors and sample size is illustrated in Figure 3. If the probe pins are all placed perfectly, ($\sigma_X = \sigma_Y = 0s$), the size of the square does not affect measurement precision; only the electrical noise affects the precision. At non-zero pin position errors the precision steadily decreases when the sample size is reduced. If the pin position error is considered to have an absolute magnitude independent of probe pitch, it is evident that the measurement error becomes inversely proportional to the electrode pitch, and a large probe would be preferred. If the square sample side length is more than approximately 12*s* the measurement precision is virtually unaffected by the size of the sample. Sample sizes very close to the probe width (6*s*), however, will have some impact on the precision.

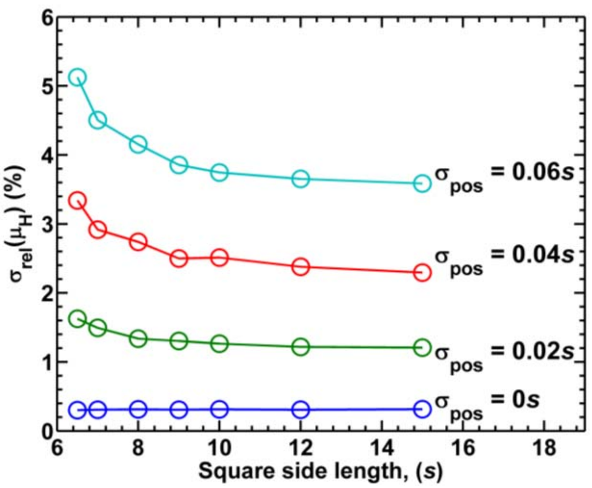


Figure 3: Relative standard deviation of measured Hall mobility, $\mu_H$ vs. square side length at different magnitudes of the pin position errors ($\sigma_X = \sigma_Y = \sigma_{pos}$), both in units of probe pitch, *s*. SNR = 3000, $\mu_H \times B = 0.01$.

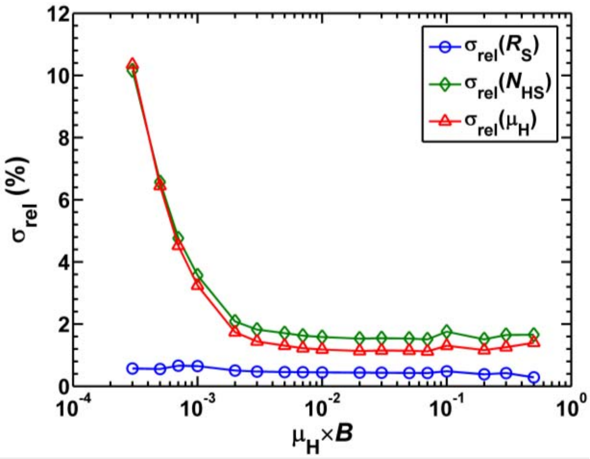


Figure 4: Relative standard deviation of $R_S$, $N_{HS}$ and $\mu_H$ vs. $\mu_H \times B$ magnitude on a semi-infinite sample. Simulation parameters: $y_0 = 0.4s$, pin position errors $\sigma_X = \sigma_Y = 0.02s$, SNR = 3000.

Measurement precision is also affected by the magnitude of $\mu_H \times B$, as shown in Figure 4. While it has virtually no impact on $R_S$ the measurement noise becomes very important for $N_{HS}$ and $\mu_H$ at low Hall signal levels.

## 6. Discussion

When evaluating the measurement method it is relevant to identify the impact of the different noise sources in various measurement situations. This is particularly useful to enable comprehensive design choices for optimum metrology performance.

In Figure 2 we observe an offset and a steady decrease of the precision on the $N_{HS}$ and $\mu_H$ parameters with measurements at increased distance from the edge. Subsequent simulations (not illustrated) clearly show that both offset and increase are mainly influenced by the pin position error, while the SNR only has a minute impact. We observe that the relative standard deviation of $\mu_H$ is less than that of $N_{HS}$, since the pin position errors on $R_S$ and $N_{HS}$ are correlated. The simulation is made with SNR = 3000 typical of measurements on a difficult sample. Thus it is evident that in all situations it is important to measure sufficiently close to the boundary, virtually independent of the electrical signal quality. In practical measurements, however, too close proximity to the sample edge increases the risk of accidentally placing a pin beyond the edge, which would obviously cause a measurement error. Aiming at approximately 4 microns ($y_0 = 0.4s$) distance to the edge is usually a good compromise when using an $s = 10$ µm M7PP.

Reducing the sample size of a square sample has relatively low impact on measurement precision. As long as the sample square is a few pitches larger than the probe the effect is minute. The pin position errors have comparably larger impact. Pin position errors are also dominant compared to the SNR; even a difficult sample without pin position errors will have a noise floor well below that due to the $\sigma_{pos} = 0.02s$, illustrated as an example in Figure 3. On samples with space enough to use a very large probe ($s >> 10$ µm) the relative pin position error may be significantly reduced thus improving the precision accordingly.

If the sample is made rectangular and reduced in the dimension orthogonal to the probe line a different source of error will occur. As the dimension is reduced the measured four-point resistances used for dual configuration position correction will become almost identical. This results in further amplification of the measurement errors when the position correction algorithm is applied, so even low noise levels can lead to unacceptable measurement errors. The investigation of this effect is beyond the scope of this study.

The dependency of the measurement precision on $\mu_H \times B$ shown in Figure 4 is characterized by a noise floor at high signal levels dominated by the pin position errors, while the finite SNR is responsible for the rapid increase at low signal levels. Increasing the magnetic flux density beyond the 1 T range typically requires impractical magnetic setups so on low mobility samples optimizing SNR is key to high precision measurements. Fundamentally the amplitude SNR is proportional to the applied current and the square root of the integration time. While integration time is relatively easy to increase the current is typically limited by the contact resistance of the specific sample. The latter is highly affected by factors such as doping level, differences in the sample/probe work functions and sample heat conduction, but not the charge carrier mobility of the sample as such.

In this study the standard filter settings of the CAPRES data analysis script was used. This includes a filtering part that removes erroneous and unreliable measurements. In the example shown in Figure 4, the simulated point at $\mu_H \times B = 3 \times 10^{-4}$ had a measurement yield of approximately 40%. Thus a poor SNR will not only reduce the precision but also the number of acceptable measurements acquired within a given time.

## 7. Conclusions and Summary

We have demonstrated the importance of crucial parameters when using the single-engage micro Hall effect measurement technique. The probe should be placed as close as possible to the boundary, as long as the probe pins are placed safely within the sample boundary. When using standard CAPRES micro probes the pin position errors would typically be the dominating source of error. However, on particularly difficult samples, typically related to sample/probe contact issues, a poor SNR may dominate the measurement error if the mobility is low.

Generally the single-engage micro Hall measurement technique is able to measure samples comparable to the probe size and mobilities ranging over several orders of magnitude with $N_{HS}$ and $\mu_H$ precision better than 2% and $R_S$ better than 0.5% for a probe pitch of $10s$.

## Acknowledgments

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