QHE samples characterization

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Abstract: We have studied different GaAs/AlGaAs heterostructures devices, used for measurements of the quantum Hall resistance R_H, to assure a standard reference of resistance with a relative uncertainty of a few parts in 10^8. The samples studied have different shapes and contacts. The objective was to select the best measurements conditions for each sample for metrological purposes. We show an example where the quantization condition was not totally fulfilled and the calibration value of our primary standards resistors differed in 5×10^{-7} from their expected values.

Keywords: QHE, standard resistance, quantum standards.

1. INTRODUCTION

The discovery of the quantum Hall effect (QHE) by K. von Klitzing in 1980 [1,2] allowed the national institutes of metrology to reach a great precision on resistance measurements, by means of the quantum Hall resistance (QHR) and the development of cryogenic current comparators (CCC). The physical studies on Hall samples gave an important deal of knowledge on electron transport, and this interest was recently renewed with quantization reported on graphene at high temperature.

2. PURPOSE

To assure quantum Hall resistance measurements with an uncertainty of 0.05 ppm or less, it is necessary to previously measure on each sample several quantities like contact resistance and quantization conditions as the residual longitudinal resistivity or the comparison of QHR values at different quantum numbers, as indicated in [3,4]. Furthermore, there are other magnitudes of interest to characterize the sample like carrier density, mobility, critical current and current or temperature dependences, which are important for knowing the behavior of each sample. These measurements allow to eliminate possible error sources in the measurement of R_H or to correct the values obtained.

The samples studied come from different laboratories as LEP, PTB, NPL and NRC, and they have different shapes and contact characteristics.

3. METHOD

We have used standard methods to study the samples, which we will call from now on: INTI 01, INTI 02, and so on. Fig 1 shows notation and geometric differences between samples.

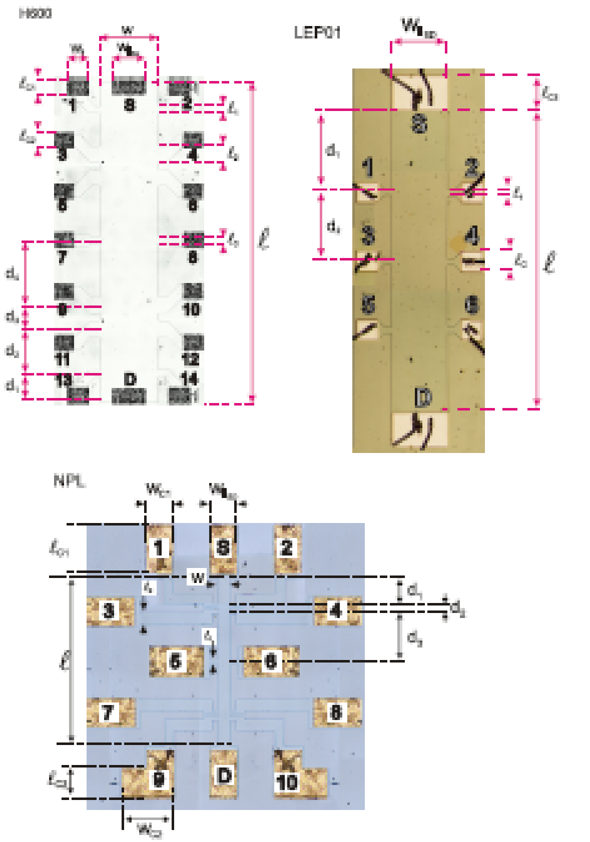

Fig. 1. Sample labeled as LEP 01 has a standard shape, while H600 and NPL have extreme characteristics. NPL has a thin body but H600 is very long instead, they also have different w_p and contact shapes.

Fig. 2. Sample INTI 02

3.1.Contact resistances

Contact resistances were measured using a three terminal technique with the sample at the QHE regime. To characterize the contact *j* we measured the voltage drop across the contact *j* and the next contact situated at the same Hall potential, V_{mj}. The current is passing through the contact *j* and one of the current contacts.

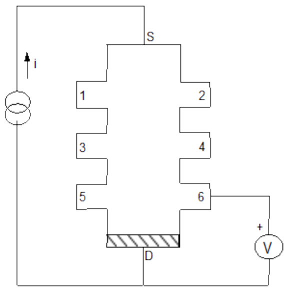

Fig. 3. Detail of the connection scheme to measure contact resistance *R*$_c$.

We measured with current in each sense in turn. For each contact *j* we have

$$\frac{V_{mj}}{i_j} = \frac{V_{lead\ j} + V_{cj} + V_{xx\ j}}{i_j} \tag{1}$$

with V_{cj} the contact voltage. $V_{lead\ j}$ was measured in each wire *j* and the value for each $R_{lead\ j}$ is known (approximately 1.5Ω). The applied current to measure the voltage contacts was 10 μA, while the current used to measure current contacts was 50 μA. If the sample is well quantized, the longitudinal resistivity ρ_{xx} can be neglected and V_{xx} is approximately zero. So measuring V_{mj} and knowing i_j we have R_{cj} with

$$R_{cj} = \frac{V_{mj} - V_{lead\ j}}{i_j} \tag{2}$$

3.2.Residual longitudinal resistivity

To evaluate the longitudinal resistivity ρ_{xx} on plateaux n=2 and n=4, we swept up the magnetic flux density while measuring the longitudinal voltage V_{xx} and the transversal voltage V_H. We looked for the minimum value V_{xx}, (usually at the middle of the plateau), and we calculated ρ_{xx} as [4]

$$\rho_{xx} = \frac{V_{xx}}{i_{SD}} \frac{w}{L} \tag{3}$$

We measured V_{xx} on both sides of the devices and for different values of *B* on each plateau.

3.3. QHR measurements

We measured V_H at the same values of *B* were V_{xx} had its minimum value. We used the two pairs of contacts to close a circuit with the same contacts used for the V_{xx} measurements. In all cases we calculated R_H as V_H/i_{SD}. To analyze some possible imperfections in the equipment or leakage resistance we compared the values of R_H at n=2 and n=4 plateaux on each device and each cooling cycle, as suggested in [4].

3.4. Carrier concentration and mobility

We have measured the carrier density *n* and the zero magnetic field mobility μ of the devices as indicated in [1] (specially chapter 2) and [6]. We calculated *n* as $n = 1/m \times 1/e$ where *m* is the slope of the R_H vs *B* graph at low field, usually to about 0.5T, and *e* is the electron charge. Once *n* was calculated it was possible to calculate the mobility at zero field as $\mu_{(B=0)} = \sigma_{SD} / n\,e$ with σ_{SD} the source drain conductivity.

3.4. Critical current

Critical current on each sample was measured applying a current i_{SD} and increasing it from 10 μA to the value where ρ_{xx} suddenly starts to increase.

4. RESULTS

We showed some examples of our measurements on next tables and figures.

Table 1. One measurement of contact resistances for sample INTI 01. In this case the contact 6 was unbounded.

R_C	**i [μA]**	**R_C [Ω]**
S	50	< 0.5
D	50	< 0.5
1	10	< 0.5
3	10	< 0.5
5	10	< 0.5
2	10	< 0.7
4	10	< 0.7
6	10	-

We have measured R_{leads} in each lead *j* and its value is known, approximately 4Ω.

To evaluate the longitudinal resistivity, we showed an example where the 2-deg was inhomogeneous:

Table 2. In this case the 2-deg was inhomogeneous. Terminals 1-3 indicate one side of the device while 2-4 indicate the other side.

Step	**ρ_{xx}□(mΩ) 1-3**	**ρ_{xx}□(mΩ) 2-4**
n=4	480	-
n=2	>5000	30

Next example shows a better cooldown. In the first case the value of calibration of one primary ESI 10kΩ resistor with QHR differed from the expected value in $5\text{x}10^{-7}$ approximately, while in the second case the value differed in $1\text{x}10^{-8}$.

Table 3. In this case the 2-deg was homogeneous and the value of calibration of our primary standards were closer to the expected value.

Step	**ρ_{xx}□(mΩ) 1-3**	**ρ_{xx}□(mΩ) 2-4**
n=2	0.68	0.80

Next table shows the relation of R_H measurements at the center of plateaux n=2 and n=4, carrier concentration at low field and zero field mobility for different samples.

Table 4. Examples of $R_H(n=2)/\ R_H(n=4)$ at the center of each plateau, carrier concentration *n* and mobility μ for different samples

Sample	**T [K] ~**	**$R_H(n=2)/\ R_H(n=4)$**	***n*** **$[10^{15}/m^2]$**	**μ[1/T]**
INTI 01	0.3	1.9995	4.93	10.5
INTI 02	4.2	1.9988	4.09	28.5
INTI 05	1.2	1.99996	4.7	23.4

Temperatures were different on each case because we have several difficulties to reach low temperatures due to different problems at the ^{3}He insert. As an example, the relation of quantization $R_H(n=2)/\ R_H(n=4)$ was not good for 4.2 K.

Finally we show one measurement of critical current for one sample at 4.2 K

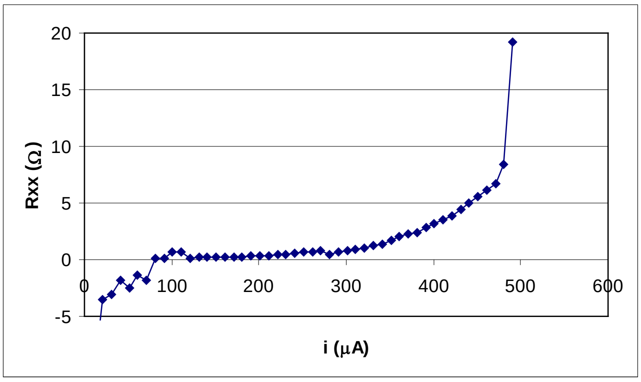

Fig. 3. Critical current for the breakdown of QHE. In this case the sample was at 4,2K

5. CONCLUSION

In order to assure an uncertainty of a few parts in 10^8 on the resistors comparison with the standard reference QHR, we are making measurements to characterize the samples. We show examples where we measured the contact resistances and the conditions of quantization of the sample after each cooling cycle, carrier density and zero magnetic field mobility to estimate the values of B for n=2 and n=4 plateaux and the critical current for the breakdown of the QHE. We showed an example where the condition of quantization was not fulfilled and the calibration value of our primary standards resistors differed in $5\text{x}10^{-7}$ from their expected values.

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