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Comparative studies of GaAs-hetero-structure samples for quantum Hall resistance standard

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Abstract : Comparative measurements of quantised Hall resistance ($R_{H,i}$, i = 2, 4) of GaAs-hetero-structure samples grown under different conditions, have been carried out at sample temperatures of 1.5 K and 0.5 K. The measurements have been done under identical conditions with both samples housed together in the same cryostat. The inter comparison of Hall plateaus with standard reference resistors $R_{R,6.45}$ and $R_{R,12.9}$ was done initially. Then further scaling down to 1 Ω, indicates that the values obtained are in better agreement within $R_{H,4}$ rather than $R_{H,2}$ among the samples with combined uncertainty better than 2×10^{-8} (1 σ estimate)

Keywords : Quantum Hall effect (integer), GaAs-hetero-structure, magnetic field Hall plateaus uncertainty and standard

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Since, the discovery of the quantum Hall effect (QHE) in 1980 [1], in certain high mobility low-dimensional semi-conductor devices, which when placed in a large magnetic field at a very low temperature of 1.0 K or below, the device exhibits quantized Hall resistance ($R_{H,i}$). Thereafter, the Comité Consultatif d'Electricité (CCE) at its meeting in September of 1988 recommended

$$R_{H,i} = \frac{R_K}{i} = \frac{h}{ie^2}$$

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where, h is a Planck's constant, e is the electronic charge and i is an integer and R_K = 25812.807 ± 0.005 Ω is the von Klitzing constant, an universal quantity assumed to be equal to the invariant quotient of the fundamental constant $\left(\frac{h}{e^2}\right)$, which came into effect on January 1990 [2] in order to obtain a world wide uniformity of resistance standard. Thus, the easy availability and evaluation of the metrological quality of different samples (Si-MOSFET and GaAs-hetero-structure) became essential for better understanding of some of the unexplained phenomenon which are not well understood even to-date [3–7]. Hence, the necessity of further study to test the consistency of experimental values previously reported on randomly collected various GaAs-hetero-structure samples, became necessary.

The purpose of the present studies is to compare the QHR ($R_{H,i}$) of different GaAs-hetero-structure samples fabricated under different conditions. The QHR is measured under identical experimental conditions with two samples at a time housed together in the same sample probe independently connected to the measuring circuit at sample temperatures of 1.5 K and 0.5 K. This also evaluates critically the present GaAs-samples under experimental conditions dedicated to metrological purpose to access non-negligible type-B error within uncertainty better than 1.2×10^{-8}. The details of the experimental apparatus have been briefly described and Hall Plateaus resistance has been compared with reference resistors $\left(R_{R,12\ 9}\,\Omega \text{ and } R_{R,6\ 45}\,\Omega\right)$.

Several GaAs-$Ga_xAl_{1-x}As$ hetero-structure samples were attempted and compared in a cryostat where two samples can be mounted at a time in the probe arrangement. Here, the two samples which were obtained from ETL (Electro-Technical Laboratory) and BIPM (Bureau International des Poids et Measures), are correspondingly marked as S-1 and S-2 respectively. The samples of BIPM were originally supplied by Laboratories d'Electronique Philips (LEP), France [8] under BIPM-EUROMET project.

The sample fabricated at LEP sometimes has a protective layer and the typical sample carrier concentration (n) is = 5.1×10^{15} m^{-2} and the values of carrier mobility (μ) is 25 T^{-1}. The sample (S-2) was mounted on TO-8 header in ETL. ETL samples (S-1) was configured in its own laboratory. The samples were classical Hall bar shaped geometry, prepared by photolithographic technique. The length and width of the sample are typically 2000 micron and 400/200 micron respectively. The contact terminals were fabricated with diffused AuGeNi contacts of good quality, ensuring access to 2DEG. These are essential for satisfactory use in precision measurement of the Hall plateau [8]. The samples were compared with standard resistors $\left(R_{R,12\ 9}\,\Omega \text{ or } 2R_{R,6\ 45}\,\Omega \text{ and } R_{R,6\ 45}\,\Omega\right)$ of known drift over several years.

The experimental apparatus is similar to the one already described [9] except the superconducting magnet which has been used, is a new magnet of 15 Tesla at 4.2 K and 17 Tesla at 2.2 K. The sample probe has been newly designed with provision to mount two samples at a time and also to cool down to temperatures 0.5 K from 4.2 K by ^{3}He pumping. Here, the measurement has been done at sample temperatures of 1.5 K and 0.5 K and the temperatures of the sample were monitored by vapour pressure thermometry and also with a germanium thermometer. The current (I_{SD}) through the device has been fed from especially fabricated highly stable Hg battery source and the sample current was maintained at 10 μA in all cases for precision measurement purpose. The electrical leads are well screened PTEF cable with high insulation resistance to keep leakage current minimum and the sample probe and its electrical insulation had been checked and the electrical leads were kept isolated from cryogenic system by mounting on kind of teflon flange to aviod any ground loop current. Besides, the system thermal noise and other system drift such as $1/f$ noise in the null detector have been taken care of by introducing frequent current reversal and periodic measurement of Hall voltage followed by reference resistors ($R_{R,12\,9}$ Ω or $2R_{R,6\,45}$ Ω and $R_{R,6\,45}$ Ω).

The detailed description of measuring circuit is given in Ref. [9] which also described the relationship in determining the unknown voltage (V_X) against the output of the potentiometer. During comparison of Hall plateaus measurement, two GaAs-samples have been mounted at a time putting one of them up-side down very close to each other. This has uniquely facilitated the comparison of Hall plateaus of two different samples in one cooling cycle at 1.5 K and also 0.5 K. The samples have been interchanged within its own top and bottom position in order to ensure there is no error due to the positioning of the samples, after every set of measurements. The Hall voltage (V_H) and the longitudinal voltage (V_{XX}) are measured and plotted by X-Y recorder against the magnetic field (B_Z) with ramping up and down as shown in Figure 1 for I_{SD} = 10 μA for typical sample (S-2) with output of nanovoltmeter Null detector (N11). Therefore, once the exact magnetic field (B_Z) of the Hall plateaus (i = 2 or 4) is known, the mid-point at the minimum of longitudinal voltage (V_{XX}) is identified.

The comparison of Hall plateaus value (i = 2, 4) has been done with reference resistor (R_R). The comparisons of $R_{H,4}$ with $R_{R,6\,45}$ Ω and of $R_{H,2}$ with $R_{R,12\,9}$ were done with modified direct current comparator (DCC) (Guildline Model-9930). The system was coupled to IBM PC-AT computer for data acquisition and also for processing of data. Once the measurement was initiated, initially, the minimum of longitudinal resistivity (ρ_{XX}) (of i = 2 or 4) of each sample was measured and the mid-point of the minimum was chosen and then the computer PC based data acquisition was carried out. The sequence of measurement has been kept in the same manner as it has been practiced in last several years in order to keep combined uncertainty within its limit. There are in general about 40 sets of readings for each cycle of run for single sample and each set of reading consisted of 16 readings with sequential reversal of polarity of current (I_{SD}). The measurement time was kept at about $4\frac{1}{2} - 5$ hours for 40 sets of reading in order to attain type A-random uncertainty better than 1.5×10^{-8}. Besides, the comparison of $R_{R,6\,45}$ to $R_{R,100}$ and then sequential measurement of scaling down to 1Ω (R_R) using cryogenic current comparator (CCC) were carried out in subsequent steps of measurement. The details of the cryogenic current comparator (CCC) system has been published elsewhere [10]. The sensitivity of the comparator (CCC) is 4×10^{-6} AT/$\phi°$, where $\phi°$ is the flux quantum. The $R_{R,6\,45}$ and $R_{R,12.9}$ reference resistors are card type YEW Type 2781 (Thomas type resistor) sealed in a metal can filled with silicon fluid and $R_{R,100}$ is a standard resistor. These are placed at a temperature regulated oil bath controlled to ± 3 mK at a nominal temperature of 20.16°C.

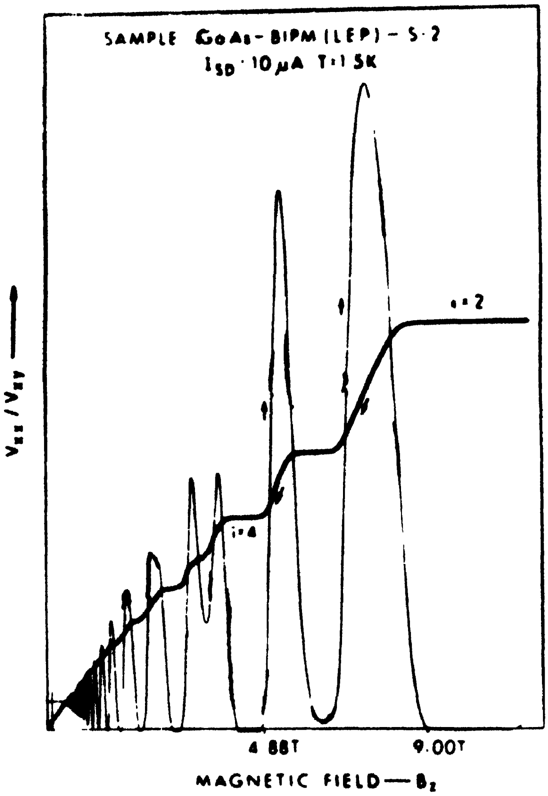

Figure 1. The recording of the Hall Voltage (V_{XY}) and the longitudinal voltage (V_{XX}) for sample S-2 as a function of magnetic field for I_{SD} = 10 μA. The arrows indicate the direction of the magnetic field ramping.

The QHR measurements for $R_{H,2}$ and $R_{H,4}$ were done in X-Y recorder as shown in Figure 1. The magnetic field were applied normal to the 2-DEG plane and the measurements were made at I_{SD} current of 10 μA for all precision measurements purpose. The respective quantized Hall plateaus were confirmed to be flat in the level of 0.08 Ω before respective measurements of $R_{H,2}$ and $R_{H,4}$. The temperature independence of $R_{H,2}$ and $R_{H,4}$ was checked by measurements made at 1.5 K and 0.5 K of the respective samples. The mid-point of the Hall plateaus of the sample S-1 and S-2 are obtained at 12.0 T and 9.65 T for i = 2 and 5.70 T and 4.60 T for i = 4 respectively at T = 1.5 K (Table 1). Also, some test of minimum of ρ_{XX} at lower or higher current (I_{SD}) and sample temperature of 0.5 K and 1.5 K were done. In view of large number of readings which were taken by computer PC in the mode of $V_{XX^-}, V_{R^+}, V_{H^+}, V_{H^-}, V_{R^-}, V_{R^-}, V_{H^-}, V_{H^+}, V_{R^+}, V_{XX}$ when the $\frac{V_{XX}}{I_{SD}}$ is low enough (typically ρ_{XX} is 0.25 mΩ) and then V_H and V_R measurements were

Table 1. Midpoints of Hall plateaus for samples.
(Sample temperature 1.5 K and Sample current I_{SD} = 10 μA)

Sample (GaAs-hetero)	mid B_Z (i = 4) (Tesla)	mid. B_Z (i = 2) (Tesla)	V_{XX} (i = 4, 2) (ppm)
S-1	5.70	12.0	0.008
S-2	4.60	9.65	0.022

carried out. The superscript (–) or (+) indicate direction of the current (I_{SD}). The results of the final set of the readings are given below

Sample	ΔR (ppm) (i = 2) $(R_{H,2} - R_{R,12.9})/R_{R,12.9}$	ΔR (ppm) (i = 4) $(R_{H,4} - R_{R,6.45})/R_{R,6.45}$
No S-1	+ 11.4170	+ 18.1984
No S-2	+ 11.4333	+ 18.1856

In case of sample no. S-1, the resistivity ρ_{XX} is 0.008 ppm (approx) for i = 2 and i = 4 respectively while ρ_{XX} is 0.022 ppm for sample no. S-2 while the sample current is 10 μA and the sample temperature 1.5 K. The uncertainty budget for the $R_{H,4}$ *vs* $R_{R,4}$ (6453.2 Ω), a comparison had been estimated accordingly (Table 2). By taking the

Table 2. Uncertainty budget in comparison for $R_{H,4}$ *vs* R_R (6453.2 Ω)
Uncertainty for the $R_{H,4}$ *vs* R_R (6453.2 Ω) comparison

Source of uncertainty	Uncertainty estimated
1) Random uncertainty	12 (× 10^{-9})
2) Potentiometer	
a) Linearity	1.3
b) Resolution of current comparator	5
3) Fractional ampere-turn measurements (linearity of DVM)	3
4) Variation of measuring current	5
5) Leakage resistance	1
6) Drift of 6453.2 Ω	4.0
RSS	16

measured values of R_H and R_R for each of the respective sample and subsequent scaling down the measurements in steps of 100 Ω, 10 Ω, 1 Ω ($R_{R,1}$) by CCC technique, the values derived for $R_{R,1}$ are the following :

$R_{R,1}\Omega = (1 - 5.6112 \times 10^{-6})$ for i = 2 in case of sample no. S-1,

$R_{R,1}\Omega = (1 - 5.6275 \times 10^{-6})$ for i = 2 in case of sample no. S-2, and $R_{R,1}\Omega = (1 - 5.6245 \times 10^{-6})$ for $i = 4$ in case of sample no. S-1,

$R_{R,1}\Omega = (1 - 5.6336 \times 10^{-6})$ for $i = 4$ in case of sample no. S-2.

In order to check consistency of values between $R_{R,12.9}$ and $R_{R,6.45}$, a set of measurements was also carried out subsequently by CCC technique and it was found to be in agreement within uncertainty of $6.75044 \times 10^{-6} \pm 0.007 \times 10^{-6}$ (1 σ estimate). The uncertainty budget of comparison of $R_{R,6.45}$ in steps to scaling down to 1 Ω is also estimated accordingly. Besides, it is necessary to make small correction for the drift of this 6453.2 Ω and 12906.25 Ω resistor during the time lag of QHR measurement and scale down process.

In conclusion, the comparison of the sample no. S-1 and S-2 could evidently show that the samples are in excellent agreement with each other within the given relative uncertainty of $< 2.0 \times 10^{-8}$. This also reconfirms the previously reported [8] invariance of QHRs with different sample characteristics. The relatively better agreement of $R_{H,4}$ as compared to $R_{H,2}$ may possibly be due to the factor that the short term drift of $R_{R,12.9}\Omega$ is relatively larger compared to $R_{R,6.45}$ or effect of high Hall electric field is more pronounced [3]. It may be mentioned here that the sample no. S-2 showed somewhat unusually high deviation (as high as 0.70 ppm) during its first measurement cycle even when we noticed that V_{XX} was very low. In the light of recent work of Jeckelmann and Jeanneret [11], the measurement may require further careful check (*e.g.* in the potential terminal contact resistance, although nothing unusual was observed in normal measurement of Hall plateaus) before any definite conclusion can be drawn. This deviation however, did not repeat in subsequent measurement sequences after thermal cycling of both the samples to room temperature, which is also reported Jeckelmann *et al* in his extensive studies of GaAs-samples [12].

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