A study of quantum Hall devices with different working magnetic fields for primary resistance metrology

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Abstract
Two kinds of quantum Hall devices with different working magnetic fields are fabricated and compared with the LEP (Laboratoires d’Electronique Philips) device, which is currently used in the primary resistance standard system of the National Institute of Metrology (NIM) of China. The comparison is made by calibrating the same 1 Ω standard resistor made by the National Measurement Laboratory of Australia using a Tinsley 100 Ω resistor as the intermediate standard and a cryogenic current comparator. The calibrated values from the NIM device with high working magnetic field and those from the LEP device agreed to within $-0.69 \times 10^{-9}$ with an uncertainty of $4.9 \times 10^{-9}$. The values from the NIM device with low working magnetic field and those from BIPM-2 agreed to within $2.5 \times 10^{-9}$ with an uncertainty of $7.1 \times 10^{-9}$.

Keywords: quantum Hall effect, resistance standards, heterojunction, cryogenic current comparator

(Some figures may appear in colour only in the online journal)
of H₃PO₄, H₂O₂ and deionized water with a volume ratio of 8:2:9. The Au(1072 nm)/Ge(528 nm)/Ni(400 nm) contact layer was grown on top of the QH mesa since it would introduce stress on the 2DEG layer and possibly result in changes in the electrical properties. The fabricated devices were mounted on home-made non-magnetic TO-8 ceramic holders. The inset of figure 2 shows a photograph of a prepared QH device.

The scales of the structure are labeled: 1 and 5 are the current pads; 2–4 and 6–8 are the voltage pads.

The heterojunction was modulation doped. The central magnetic flux density $B_{2c}$ of NIM-2 is only 6.88 T for the NIM QHR standard system. NIM-1 is designed to replace BIPM-2 as the standard device. The mobility of NIM-1 is lower than that of BIPM-2. The magnetic field $B$ at 1.5 K with a 10 μA bias current is 2 T for BIPM-2 and NIM-1. The mobility of NIM-1 is lower than that of BIPM-2. NIM-1 is designed specifically for a low magnetic field measurement.

The BIPM-2, NIM-1 and NIM-2 devices were then characterized in the NIM QH resistance standard system which consists of an Oxford magnet (16 T), a high-accuracy current source, an EM N11 voltage meter and the CCC. The devices were slowly cooled to 1.5 K. Three important device parameters, namely central magnetic flux density $B_{2c}$, residual longitudinal resistance $R_{xx}$ at $B_{2c}$, and contact resistance $R_c$ at the $i=2$ plateau, were measured.

The longitudinal resistance $R_{xx}$ is equal to $V_{xx}/I_{15}$, where $V_{xx}$ can be $V_{24}$ or $V_{86}$ obtained from the EM N11 voltage meter, and $I_{15}$ is the current flowing through the device. The central magnetic flux density $B_{2c}$ at the $i=2$ plateau is determined by sweeping the magnetic flux density $B$ and measuring the longitudinal resistance $R_{xx}$; the typical bias current $I_{15}$ used in this process is 10 μA. Once $B_{2c}$ is determined, we set the magnetic field to $B_{2c}$ and measure the residual longitudinal resistance at $B_{2c}$. In this process $I_{15}$ is set to 38 μA. The contact resistance $R_c$ is measured using a three-terminal technique. The width of the $i=2$ plateau $ΔB_2$, mobility $μ$ and carrier concentration $n$ of the devices were calculated from the $R_{xx}$ vs $B$ curves. The characterized parameters of the three devices are listed in table 2.

Figure 2 shows the $R_{xx}$ of the devices BIPM-2, NIM-1 and NIM-2 as a function of applied magnetic flux density at 1.5 K with bias current $I_{15} = 10$ μA. The inset shows a prepared QH device mounted on the NIM-made TO-8 carrier, which is composed of 8 BeCu pins, a ceramic plate and a Teflon cap.

3. Measurement

The BIPM-2, NIM-1 and NIM-2 devices were then characterized in the NIM QH resistance standard system which consists of an Oxford magnet (16 T), a high-accuracy current source, an EM N11 voltage meter and the CCC. The devices were slowly cooled to 1.5 K. Three important device parameters, namely central magnetic flux density $B_{2c}$, residual longitudinal resistance $R_{xx}$ at $B_{2c}$, and contact resistance $R_c$ at the $i=2$ plateau, were measured. The longitudinal resistance $R_{xx}$ is equal to $V_{xx}/I_{15}$, where $V_{xx}$ can be $V_{24}$ or $V_{86}$ obtained from the EM N11 voltage meter, and $I_{15}$ is the current flowing through the device. The central magnetic flux density $B_{2c}$ at the $i=2$ plateau is determined by sweeping the magnetic flux density $B$ and measuring the longitudinal resistance $R_{xx}$; the typical bias current $I_{15}$ used in this process is 10 μA. Once $B_{2c}$ is determined, we set the magnetic field to $B_{2c}$ and measure the residual longitudinal resistance at $B_{2c}$. In this process $I_{15}$ is set to 38 μA. The contact resistance $R_c$ is measured using a three-terminal technique. The width of the $i=2$ plateau $ΔB_2$, mobility $μ$ and carrier concentration $n$ of the devices were calculated from the $R_{xx}$ vs $B$ curves. The characterized parameters of the three devices are listed in table 2.

Figure 2 shows the $R_{xx}$ of the devices BIPM-2, NIM-1 and NIM-2 as a function of $B$ at 1.5 K with a 10 μA bias current. The $B_{2c}$ of NIM-1, which is 10.24 T, is close to that of BIPM-2 due to the similar carrier concentration. The magnetic field width at the $i=2$ plateau $ΔB_2$ is about 2 T for BIPM-2 and NIM-1. The mobility of NIM-1 is lower than that of BIPM-2. NIM-1 is designed to replace BIPM-2 as the standard device for the NIM QHR standard system.

NIM-2 is designed specifically for a low magnetic field resistance standard system. The $B_{2c}$ of NIM-2 is only 6.88 T and the corresponding carrier concentration is as low as $3.32 \times 10^{15}$ m⁻². $ΔB_2$ is only about 0.89 T for NIM-2 because of the closer Landau levels due to the low carrier concentration; the mobility is 33.2 T⁻¹. 

### Table 1. Layer structures of the heterojunction.

| Layers | Thickness (nm) |
|--------|----------------|
| GaAs:Si | NIM-1 | NIM-2 |
| 1.4 × 10¹⁸ cm⁻³ | 10 | 10 |
| Al₀.₂₈Ga₁₋₀.₂₈As:Si | 50 | 50 |
| 1.4 × 10¹⁸ cm⁻³ | 10 | 14 |
| Al₀.₂₈Ga₁₋₀.₂₈As (spacer) | 500 | 500 |
| GaAs | 15/185 | 15/185 |
| GaAs/Al₀.₂₈Ga₁₋₀.₂₈As | 200 | 200 |
| GaAs buffer | 3 inch | 3 inch |

Figure 1. Structure of the NIM-1 and NIM-2 devices: the pink and blue layers represent the Hall bar and the contacts respectively. The scales of the structure are labeled: 1 and 5 are the current pads; 2–4 and 6–8 are the voltage pads.

Figure 2. Longitudinal resistance $R_{xx}$ of the devices BIPM-2, NIM-1 and NIM-2 as a function of applied magnetic flux density at 1.5 K with bias current $I_{15} = 10$ μA. The inset shows a prepared QH device mounted on the NIM-made TO-8 carrier, which is composed of 8 BeCu pins, a ceramic plate and a Teflon cap.
at with a Tinsley 100 Ω transfer resistor as the intermediate standard. Vxx less than 0.63 m (400:31 and a 0.5 V bridge voltage. The QH voltage
100
Ω
device was calibrated. Figure 3 shows the calibration procedure.
First we used these three QH devices to calibrate a Tinsley standard resistor. Figure 3 shows the calibration procedure.

Table 2. Characterization of the BIPM-2, NIM-1, and NIM-2 devices at 1.5 K and the j = 2 plateau.

| Devices     | $B_{\infty}$ (T) | $\Delta B_{\infty}$ (T) | $\mu$ (T$^{-1}$) | $n$ (10$^{15}$ m$^{-3}$) | $R_{\text{xx}}$ at $B_{\infty}$ (mΩ) By N11 | $R_c$ (Ω) |
|--------------|-----------------|-----------------|----------------|----------------|----------------------------------|----------|
| NIM-1        | 10.24           | 1.99            | 40.4           | 4.94           | 0.63                             | 1.6      |
| BIPM-2       | 10.25           | 1.99            | 56.4           | 4.95           | 0.63                             | 1.3      |
| NIM-2        | 6.88            | 0.89            | 33.2           | 3.32           | 0.40                             | 2.0      |

For all three devices, the longitudinal resistance $R_{\text{xx}}$ at $B_{\infty}$ is less than 0.63 mΩ ($V_{\text{xx}} < 0.02 \mu V$) which is close to the measurement limit of the EM N11 voltage meter, as affected by the lab conditions. $R_c$ is measured using a three-wire method at $B_{\infty}$, so both the wire resistance and $R_c$ are included. The $R_c$ values of the three devices are all < 2 Ω, which is small enough for metrological measurements [17, 18]. $R_{\text{xx}}$ and $R_c$ show that the NIM devices have been completely quantized and can be used as the standard devices in the QHR standard system.

We have compared the devices BIPM-2, NIM-1 and NIM-2 by undertaking a calibration measurement of an NML 1 Ω standard resistor. Figure 3 shows the calibration procedure. First we used these three QH devices to calibrate a Tinsley 100 Ω transfer resistor using a CCC with a winding ratio of 400:31 and 0.5 V bridge voltage. The QH voltage $V_{\text{xx}}$ was achieved from voltage pads 3 and 7, and $I_{15} = 38 \mu A$. Then we used the calibrated Tinsley 100 Ω resistor to calibrate the NML 1 Ω standard resistor using the CCC with a winding ratio of 400:4 and a 0.05 V bridge voltage. The calibration values of the NML 1 Ω standard resistor by BIPM-2, NIM-1 and NIM-2 are labeled as $R_{\text{BIPM}}$, $R_{\text{NIM-1}}$, and $R_{\text{NIM-2}}$. Both the Tinsley 100 Ω and 1 Ω resistors were kept in a 293 K oil bath.

The calibration results shown in figure 4. The vertical axis represents the relative difference of the calibration values, expressed as $(R_{\text{NIM}} - R_{\text{BIPM}})/R_{\text{BIPM}}$. For NIM-1 and BIPM-2, the calibration values agreed to within $-0.69 \times 10^{-9}$, for NIM-2 and BIPM-2, they agreed to within $2.5 \times 10^{-9}$. For this calibration measurement, the combined standard uncertainty $u_c$ includes the uncertainty $u_1$ of the Tinsley 100 Ω resistor, the uncertainty $u_2$ of the NML 1 Ω resistor and the system uncertainty $u_3$. and $u_c = (u_1^2 + u_2^2 + u_3^2)^{1/2}$, $u_3$ is $0.24 \times 10^{-9}$ [19], and $u_1$ is $2.5 \times 10^{-9}$, $0.6 \times 10^{-9}$ and $1.7 \times 10^{-9}$ for the values from BIPM-2, NIM-1 and NIM-2, respectively. $u_2$ is $6.1 \times 10^{-9}$, $4.9 \times 10^{-9}$ and $6.9 \times 10^{-9}$ for the corresponding values from BIPM-2, NIM-1 and NIM-2. So $u_c$ for $R_{\text{BIPM}}$, $R_{\text{NIM-1}}$ and $R_{\text{NIM-2}}$ is $6.6 \times 10^{-9}$, $4.9 \times 10^{-9}$ and $7.1 \times 10^{-9}$, respectively. These values are a little large for the three devices because of the two-stage calibration chain.

4. Conclusions

Single quantum Hall devices with high (above 10 T, NIM-1) and low (below 7 T, NIM-2) working magnetic flux density were fabricated and characterized. The two devices were compared with the LEP-made device (BIPM-2) by calibrating the same NML 1 Ω standard resistor. The relative differences between the two calibrated values given by NIM-1 and BIPM-2, and NIM-2 and BIPM-2, are $-0.69$ parts in $10^9$ and $2.5$ parts in $10^9$ respectively. The calibration results show that NIM-made devices can be used as standard devices for the quantum Hall resistance standard system.

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