Quantum Hall devices for the primary resistance standard based on the GaAs/Al_xGa_{1-x}As heterostructure

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Quantum Hall devices for primary resistance metrology based on the GaAs/Al_xGa_{1-x}As heterostructure were fabricated and compared with the devices from international metrology organization International Bureau of Weights and Measures (BIPM) by calibrating the same 100 Ω transfer standard resistor with a cryogenic current comparator. Relative deviation between NIM-made device NIM-C1 and BIPM-made device BIPM-1 was -4.49 parts in 10⁹ with an uncertainty of 3.63 parts in 10⁹ which indicated NIM-C1 satisfied the requirement for the primary resistance standard.

Keywords: Quantum Hall effect; resistance standard; calibration; resistance metrology.

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1. Introduction

The primary resistance standard was quantized by Quantum Hall (QH) effect with in terms of Planck constant h and elementary charge e to replace the physical resistance standard.^{1,2} QH standard devices with an accuracy of 10⁻⁹ have been realized by GaAs/Al_xGa_{1-x}As heterostructures.³⁻⁵ and also epitaxial monolayer graphene.^{6,7} In NIM, the QH devices for national resistance standard system were previously provided by international metrology organization International Bureau of Weights and Measures (BIPM) based on GaAs/Al_xGa_{1-x}As heterostructures.⁸ NIM has begun to fabricate the self-made QH devices both on graphene and GaAs substrate.⁹⁻¹¹ to guarantee the stability and independence of the national resistance

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standard. In this paper, the NIM-made QH device based on the GaAs/Al_xGa_{1-x}As heterostructures were fabricated and compared with the BIPM device.

2. Device Fabrication

The GaAs/Al_xGa_{1-x}As heterostructure was grown on a GaAs substrate by molecular beam epitaxy with the designed structure,¹² as described in the previous work.¹¹ The central working magnetic field (B_{2c}) of the filling factor $i = 2$ QH resistance plateau was designed to be above 9 T by adjusting the carrier doping concentration. The structure of the QH device¹³ was shown in Fig. 1. The pads 1 and 5 were the current pads, and 2–5, 6–8 were the voltage pads. Red parts were the Hall bar and the blue areas were the contacts. The blue region outside was for wire bonding.

The dimension of the Hall bar was $2400 \mu\text{m} \times 400 \mu\text{m}$ defined by a UV lithography process and wet etch using a solution of H₃PO₄, H₂O₂ and demonized water with a volume ratio 8:2:90. The contacts were formed by sequential e-beam deposition of 1072 Au, 528 Ge and 400 nm Ni, followed by a rapid thermal annealing process in N₂/H₂ to form ohmic contacts.¹⁴ The optical image is shown in the inset of Fig. 2.

Fig. 1. (Color online) The structure of NIM-C1 QH devices: The pink and blue layers represent Hall bar and the contacts, respectively.

Fig. 2. (Color online) The longitudinal resistance R_{xx} versus magnetic flux density B of NIM-C1 at 1.5 K with a bias current $I_{15} = 10 \mu\text{A}$. The inset is the NIM-made NIM-C1.

3. Measurements

NIM-C1 and BIPM-1 were measured in the primary resistance standard system equipped with an Oxford magnet (14 T), home-made high accuracy current source, EM N11 voltage meter and a cryogenic current comparator (CCC). The typical longitudinal resistance R_{xx} versus magnetic flux density B curve of NIM-C1 at 1.5 K with a bias current $I_{15} = 10 \mu\text{A}$ is shown in Fig. 2. The B_{2c} , the width of $i = 2$ plateau ΔB_2 , the mobility μ , the carrier concentration n , the residual longitudinal resistance R_{xx} and contact resistance R_c at the $i = 2$ plateau are shown in Table 1. R_{xx} was achieved by $((V_{24}(I_{15+}) - V_{24}(I_{15-}))/2I_{15})$ with the current direction of I_{15} ($38 \mu\text{A}$) was reversed at B_{2c} . R_c was measured by a three-terminal method.

To verify the performance, the self-made NIM-C1, NIM-C1 and BIPM-1 were compared by calibrating a SR102 100 Ω transfer standard resistor by a CCC with the winding ratio 6066:47. The calibration chain is shown in Fig. 3. R_{xy} (V_{37}/I_{15}) is the QH resistance. NIM-C1 and BIPM-1 worked at 1.5 K with the bias current 38 μA , and SR102 is kept at 20°C in an oil bath.

For the BIPM-1, the calibration value R_{BIPM} was $100 \times (1 + 0.077549 \times 10^{-6})$ with the uncertainty u_1 of 1.82×10^{-9} ; For the NIM, the calibration value R_{NIM} was $100 \times (1 + 0.073062 \times 10^{-6})$ with the uncertainty u_2 of 3.14×10^{-9} . The relative difference of the calibration values expressed as $(R_{\text{NIM}} - R_{\text{BIPM}})/100$ was $-4.49 \times$

Table 1. Characterization of NIM-C1 at 1.5 K at the $i = 2$ plateau.

Devices	B_{2c} (T)	ΔB_2 (T)	μ (T^{-1})	n (10^{15}m^{-2})	R_{xx} (m Ω) By N11	R_c (Ω)
NIM-C1	9.81	1.88	45.5	4.73	0.26	1.4

Fig. 3. (Color online) The calibration chain of the SR102 100 Ω transfer standard resistor by a CCC.

Table 2. Standard uncertainties in the calibration process of the 100 Ω transfer standard resistor.

Source	Type	Uncertainty/ 10^{-9}
NIM-C1	A	3.14
BIPM-1	A	1.82
NIM QHR standard system	A, B	0.24 ¹⁵
$(R_{\text{NIM}} - R_{\text{BIPM}})/100$		3.63

10^{-9} . The uncertainty of the NIM QHR standard system u_3 was 0.24×10^{-9} . Then the combined standard uncertainty $u_c = \text{sqrt}(u_1 \times u_1 + u_2 \times u_2 + u_3 \times u_3)$ was 3.63×10^{-9} , as shown in Table 2. The possible reason for the relative discrepancy is larger than the relative measurement uncertainty in this paper which was the resistance value of the artificial 100 Ω transfer resistor shifted and this shift was small and random.

4. Conclusions

Self-made QH device was fabricated for the primary resistance standard system and compared with the BIPM standard device by calibrating the same SR102 100 Ω transfer standard resistor. The relative difference of the calibrated values given between the two devices agreed to -4.49 parts in 10^9 with an uncertainty of 3.63 parts in 10^9 . The calibration result showed that NIM-self-made device can act as the standard device for the QH resistance standard system.

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