In electrical quantum metrology the electrical units are referred to natural constants like the electronic charge $e$ and the Planck constant $h$. Namely, the quantum Hall effect (QHE) links the unit Ohm to $R=\frac{h}{e^2}$ [1]. For this quantum Hall resistance the von Klitzing constant $R_K=\frac{h}{e^2}$ was introduced and its value was recommended in the year 1990 as $R_{K-90}=25812.807$ Ω. For realizing such quantum resistance standards, QHE devices with a two-dimensional electron gas (2DEG) in an Al(Ga)As heterostructure are widely used. In such samples, metrological calibrations are carried out at filling factor $i=2$, meaning that the corresponding quantized resistance has a value of $R_K/2 \approx 12.9$ kΩ [2,3]. Combining quantum Hall devices in series or in parallel with the help of the multiple link technique [4] allows for tailoring of quantum standards with almost arbitrary resistance values and also over a broad resistance range, i.e. the realization of decadic quantum resistors [5]-[8]. This would increase the number of well known resistance ratios for the validation of resistance bridges and comparator measurement systems. Moreover, quantum Hall array resistance standards (QHARS) might simplify the calibration of standard platinum resistors by shortening the calibration chain. On the other hand, QHE arrays could act as a stable high-precision traveling standard [9]. And, finally, serial QHE-arrays could benefit from their noise behavior which is for resistance values larger than 100 kΩ, expected to be much lower than for equivalent wire resistors. Such low noise, low temperature coefficient, high resistance devices of several MΩ would improve the signal-to-noise ratio in a low current experiment, as, i.e. a direct realization of the quantum metrological triangle experiment [10].
two connections of the voltage terminals are present: One direct connection and one cross connection. The direct connection serves to add up the Hall voltages $U_{xy}$ of the two elements measured between terminal 1 and 4 and thus to realize a serial Hall resistor. The additional cross connection serves to suppress the influence of the non negligible contact resistance of the interconnect on the serial Hall voltage. Without the cross connection a voltage measurement between the voltage terminals 1 and 4 would yield a value $U_{1,4} = 2U_{xy} + IR_c$ where $U_{xy}$ is the Hall voltage at filling factor $i$ and $R_c$ is the resistance of the current interconnect. The cross connections serve to reduce the contribution of the contact resistance to $U_{1,4}$: Each additional connection carries a current which is smaller than the current in the preceding connection by a factor $R_C/(R_K/i)$ which is in the order of $10^{-4}$ for typical $R_C$ values of 1 Ω. Hence, high precision realization of the serial Hall resistance $R_{1,4} = U_{1,4}/I = 2(R_K/i)$ is possible. Note however, that this effect of the cross connections only occurs if both the current and voltage interconnections between the two Hall bars terminate on the same equipotential line. Under quantized Hall conditions the two-terminal voltage drop across the Hall bar occurs at two opposing corners of the current terminals, the so called hot spots. The Hall bar edges between these two hot-spots are on the same potential as indicated by the full black and dashed red lines.

Figure 1. Series connections of two Hall elements with additional cross-connections, see text.

Our samples were grown at a growth temperature of 620°C by solid source MBE on 2” GaAs wafers of a set of 10 nominally identical heterostructures for complete-wafer processing. The heterostructures with a deep two-dimensional electron gas 72 nm below the surface had an electron density of $n \sim 5 \cdot 10^{11}$ cm$^{-2}$ with an electron mobility of $\mu \sim 3.94 \cdot 10^5$ cm$^2$/Vs. These values were extracted from magnetotransport measurements at 2.2 K of 4 mm × 4 mm pieces in van-der Pauw (vdP)-geometry cleaved from the center of the wafers. From these heterostructures we processed lithographic serial arrays consisting of ten rectangular Hall bars having linear dimensions of 1.05 mm × 0.31mm. The design was directly written by a laser lithographic pattern generator Heidelberg instruments DWL66fs and the sample fabrication involved a multiple layer process.

Figure 2. (a) Zoom-in of the interconnection area with SiO$_2$ layer on top of the Au wiring. (b) Electron micrograph of the interconnections.
In a first step, the Hall bars and the alignment markers were defined by a 100 nm deep slow wet etch process. Afterwards standard AuGeNi ohmic contacts with eutectic AuGe and Ni were thermally evaporated and annealed at 450°C for 55 seconds. Then the wiring layer was produced by evaporating 10 nm Ti and 70 nm Au with a connection line width of 10 µm. As discussed before, the serial array needed interconnections for compensating the contact resistances. Hence, we have realized thereafter an insulation layer for the interconnections of the Au wiring with a layer of 100 nm SiO$_2$ deposited by a PECVD in a lift-off process. The PECVD process was performed in three steps with a rotation of the sample after each turn to avoid bad insulation due to pinholes. The interconnection area is shown in Fig. 2. Two crossing gold wirings separated by SiO2 (not visible) are shown. The electron micrograph well visualizes the steepness of the insulator edge after lift-off. Nevertheless, by realizing the upper wire by a 200 nm Au layer a good bridge connection over the insulator edge can be ensured.

The resulting magnetotransport data for one of our samples at $T = 0.3$ K is presented in Fig. 3. Here an array of 10 Hall bars connected in series according to the scheme of Fig. 1 is investigated. Within the resolution of our pre-characterization, which was better than 60 mΩ, we found for the $i=2$ plateau vanishing longitudinal resistivities over the corresponding magnetic field range. This indicated the absence of parasitic bulk conductivity and demonstrates the good quantization of the 2DEGs. Comparing the $R_{xx}$-curves of the two Hall bars at the ends of the array, they fitted quite well to each other within a deviation of less than 2 % in the oscillation period demonstrating the homogeneity of the serial array. The Hall curves showed a flat $i=2$ resistance plateau with a value of 129.07 kΩ $= 10(R_K/2)$ as expected and a width of 1.3 T centered around 9.55 T. Interestingly, reversing the magnetic field direction ($B_\uparrow$) reduced the quantized value of the resistance plateau by exactly the contribution of two Hall bars in the series connection. The reason for this behavior is the shift of the quantum Hall hot spots upon field reversal and the related redistribution of the edge state current paths which results in a partial exchange of the role of the voltage and current terminals. As a consequence the last two Hall bars do not contribute to the total serial voltage. A more detailed discussion of this effect can be found in reference [11,12]. High-precision measurements of $R_H$ were performed at $T = 80$ mK and a current of $I = 1$ µA by means of a cryogenic current comparator (CCC) bridge [13,14] with our well-known QHE standard P137-18.

![Figure 3](image_url)  
**Figure 3.** Experimental value of the transverse and longitudinal resistance of lithographic serial 10-Hall bar array for both field configurations, $T=0.3$ K. Inset shows a photograph of the sample mounted in a TO8 socket suitable for precision measurements.
The quantization of the \(i=2\) resistance was measured at the center of the plateau yielding a relative deviation of \(1.5 \times 10^{-7}\) from the expected value \(10(R_K/2)\). The reasons for this deviation are subject of further investigation. Possible reasons could be e.g. an imperfect insulation of the interconnection region or a too high Ohmic contact resistance in some of the Hall bars of the array.

3. Conclusion
In summary, we have investigated a serial array of ten quantum Hall bars as a Quantum Hall Array Resistance standard. We were able to process samples showing a relative deviation of \(1.5 \times 10^{-7}\) from the expected resistance value of \(10(R_K/2)\). For future applications in electrical quantum metrology a deviation of \(10^{-8}\) must be obtained. Such values seem feasible upon optimization of fabrication parameters.

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