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A quantum transresistance amplifier for traceable current measurements in the microampere range

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***Abstract*—This work presents a transresistance amplifier for traceable current measurements in the microampere range with an accuracy at the 10^{-7} level, and two experiments planned at the Istituto Nazionale di Ricerca Metrologica and at the Korea Research Institute of Standards and Science to verify the accuracy of the transresistance amplifier with a single quantized Hall resistance standard and a quantized Hall array resistance standard, respectively.**

***Index Terms*—Current measurement, electrical resistance measurement, low-noise amplifiers, calibration**

I. Introduction

A *transresistance amplifier* (TRA) is an electronic device that converts a current into a voltage with a gain called *transresistance*. TRAs are routinely employed to measure small DC electric currents, from the sub-femtoampere range to the milliampere range, because a TRA minimizes the input burden error and the output loading error compared to the direct injection of a current into a resistance standard. However, accurate current measurements require the calibration of the transresistance, with traceability to the International System of Units. The calibration is typically performed by injecting a set of one or more calibrated currents into the TRA.

The authors at Politecnico di Torino (POLITO), Turin, Italy, have recently designed a TRA [1] for which the traceability of current measurements in the microampere range is ensured at the 10^{-7} level by the TRA design and by an external calibrated resistance standard. This can be either a room-temperature calibrated artifact resistance standard, a quantized Hall resistance standard (QHRS) or a quantized Hall array resistance standard (QHARS). In the last two cases, this concept opens up for the possibility of accurate calibrationless current measurements.

This work presents two experiments planned in spring 2026 at the Istituto Nazionale di Ricerca Metrologica (INRIM), Turin, Italy, and in summer 2026 at the Korea Research Institute of Standards and Science (KRISS), Daejeon, Republic of Korea, to verify the operation and the accuracy of the TRA with, respectively, a single-element QHRS with nominal value $R_\mathrm{H} = R_\mathrm{K}/2 \approx 12\,906\,\Omega$, R_K being the von Klitzing constant, and a one-hundred-element QHARS with nominal value $100R_\mathrm{H} \approx 1.2906\,\mathrm{M\Omega}$.

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II. Transresistance Amplifier

The TRA has been designed to operate in either of two configurations, one with a $12.9\,\mathrm{k\Omega}$ QHRS and one with a $1.29\,\mathrm{M\Omega}$ QHARS, with the same target accuracy. The core is a four-stage composite amplifier with open-loop gain greater than 3×10^7. A T compensation network ensures the TRA stability by preventing self-oscillation with input and output capacitive loads up to $3\,\mathrm{nF}$, allowing the use of long cables with both QHRS and QHARS. The T network has been designed to have an effective leakage resistance greater than tens of teraohms. The high open-loop gain and leakage resistance result in a relative DC gain error at the 10^{-7} level, which implies that the input current relatively differs from the current crossing the feedback resistor by less than 10^{-7}. The TRA provides an output voltage range of $\pm 10\,\mathrm{V}$ with a bandwidth of about $32\,\mathrm{kHz}$ when operating with the QHRS and of about $1.6\,\mathrm{kHz}$ when operating with the QHARS. Two prototypes have been assembled and characterized in [1], with particular attention to the leakage resistance of the compensation network, the input impedance, and the output offset and its temperature dependence. The gain accuracy was verified with room-temperature resistance standards, demonstrating consistency with the target accuracy level.

The TRA can be connected to a QHRS or a QHARS as represented in Fig. 1. The TRA converts the input current i_S into an output voltage $v_\mathrm{O} = R_\mathrm{m} i_\mathrm{S}$, where the transresistance

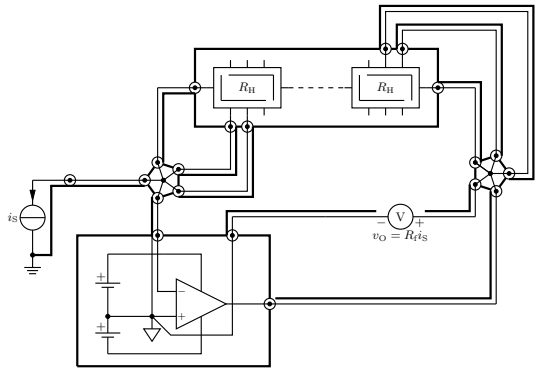


Fig. 1. Schematic of the TRA setup for currents up to $50\,\mu\mathrm{A}$ with transresistance $R_\mathrm{f} = R_\mathrm{H}$ or up to $1\,\mu\mathrm{A}$ with $R_\mathrm{f} = 100R_\mathrm{H}$. The quantum devices are connected to two star points with triple connections.

R_m ideally equals the feedback resistance R_f. The R_f is defined across two star points connected to the TRA input and output and implemented by either a QHRS or a QHARS connected to the star points by means of triple connections. This configuration suppresses the errors caused by interconnection resistances [2]. The polarity of i_S is periodically reversed to cancel the errors due to offsets and bias current [3].

III. Quantum Hall Resistance Standards

The QHRS for the INRIM experiment is a p-type epitaxial graphene device molecularly doped with the acceptor F4-TCNQ, fabricated in the cleanroom facility of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig [4]. The device is about $1600\,\mu\mathrm{m} \times 400\,\mu\mathrm{m}$ and the distance between adjacent contacts is $400\,\mu\mathrm{m}$. The device is mounted on a TO-8 socket.

The QHARS for the KRISS experiment was purpose-designed and fabricated by the Research Institutes of Sweden (RISE), Borås, Sweden. The QHARS, shown in Fig. 2, is based on epitaxial graphene, fabricated using lithography techniques described in detail elsewhere [5]. The individual Hall bars are $400\,\mu\mathrm{m} \times 200\,\mu\mathrm{m}$ and are connected using superconducting NbN leads. The entire array consists of 10 segments of subarrays, each containing 10 Hall bars, for a grand total of 100 series-connected elements. Each subarray can be addressed individually via multiterminal connections.

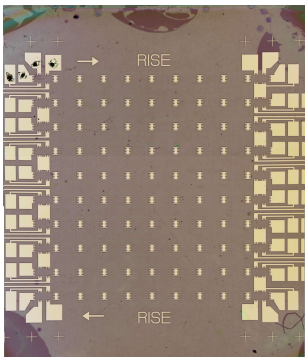


Fig. 2. Optical micrograph of the $7\,\mathrm{mm} \times 7\,\mathrm{mm}$ QHARS SiC chip.

IV. Experimental Setups

The common features of the setups are shown in Fig. 1.

The INRIM setup is designed to measure currents up to $50\,\mu\mathrm{A}$ employing a QHRS as feedback resistance, such that $R_\mathrm{f} = R_\mathrm{H}$. The input current i_S is generated by a bipolar Yokogawa GS200 DC voltage source and a temperature-controlled $12.906\,\mathrm{k\Omega}$ resistance standard R_s (VPG H-series oil-filled foil resistor operating at $29\,^\circ\mathrm{C}$). The QHRS is maintained at high magnetic field ($6\,\mathrm{T}$) in a Leiden Cryogenics dry dilution refrigerator CF-CS110, providing an experimental space at approximately $3.6\,\mathrm{K}$. A calibrated ratiometric long-scale digital multimeter (DMM) Fluke 8588A measures the ratio between the output voltage v_O and the voltage v_S across R_s. This ratio is compared with the calibrated resistance ratio $R_\mathrm{f}/R_\mathrm{s}$ to determine the TRA gain error. The ratio $R_\mathrm{f}/R_\mathrm{s}$ is calibrated by employing a DC current comparator bridge (DCC) and the custom-made STD VH01 transfer resistance standard R_t with a nominal value of $1\,\mathrm{k\Omega}$, composed of ten parallel Vishay VHA 512T $10\,\mathrm{k\Omega}$ components (tolerance $\pm 0.005\,\%$) temperature-controlled at about $27\,^\circ\mathrm{C}$. The ratio $R_\mathrm{f}/R_\mathrm{s}$ is thus obtained by combining the results of the ratio measurements $R_\mathrm{f}/R_\mathrm{t}$ and $R_\mathrm{s}/R_\mathrm{t}$ consecutively performed in the same $12.9:1$ ratio condition and at the same TRA working current.

The KRISS setup is designed to measure lower currents up to $5\,\mu\mathrm{A}$ employing the RISE QHARS ($1.29\,\mathrm{M\Omega}$) as feedback resistance. The QHARS is kept in a wet cryomagnet at the liquid helium temperature of 4.2 K and a magnetic field up to 12 T. The input current i_S is generated by an *ultrastable low-noise current amplifier* (ULCA) [6], configured for generation in an extended current range [7] and driven by a bipolar DC voltage source Yokogawa GS200. The TRA output voltage v_O is measured by a calibrated long-scale DMM Keysight 3458A and the input current is determined as $i_\mathrm{S} = v_\mathrm{O}/R_\mathrm{f}$. The same DMM measures also the output voltage $v_\mathrm{O}^\mathrm{ULCA}$ of the current monitor output of the ULCA and the input current is also determined as $i_\mathrm{S}^\mathrm{ULCA} = v_\mathrm{O}^\mathrm{ULCA}/R_\mathrm{iv}$, where $R_\mathrm{iv} \approx 1\,\mathrm{M\Omega}$ is the ULCA calibrated internal resistance. The current i_S is then compared with $i_\mathrm{S}^\mathrm{ULCA}$. The DMM is alternately switched between the two outputs by means of a scanner.

V. Conclusion and Outlook

The TRA designed and tested in [1] will be used to measure currents in the microampere range, converting them into voltages by employing quantized Hall resistance standards as transresistance. Two experiments are described, which aim at an uncertainty level of 10^{-7}. The first will employ a QHRS operating at a maximum current of $50\,\mu\mathrm{A}$, the second will employ a 100-element series QHARS operating at a maximum current of $1\,\mu\mathrm{A}$. These are the first experiments of this kind and the results will be presented at the time of the conference.

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References

[1] M. Musso and M. Ortolano, "Design and implementation of a transresistance amplifier for accurate current measurements in the microampere range," 2026, submitted.

[2] F. Delahaye, "Series and parallel connection of multiterminal quantum Hall-effect devices," *J. Appl. Phys*, vol. 73, pp. 7914–7920, 1993.

[3] Keithley, "Low level measurements handbook," Feb. 2016.

[4] Y. Yin *et al.*, "Quantum Hall resistance standards based on epitaxial graphene with p-type conductivity," *Appl. Phys. Lett.*, vol. 125, p. 064001, 2024.

[5] H. He *et al.*, "Accurate graphene quantum Hall arrays for the new International System of Units," *Nat. Commun.*, vol. 13, pp. 1–9, 2022.

[6] D. Drung, C. Krause, U. Becker, H. Scherer, and F. J. Ahlers, "Ultrastable low-noise current amplifier: A novel device for measuring small electric currents with high accuracy," *Rev. Sci. Instrum.*, vol. 86, 2015.

[7] D. Drung and C. Krause, "Ultrastable low-noise current amplifiers with extended range and improved accuracy," *IEEE Trans. Instrum. Meas.*, vol. 66, pp. 1425–1432, 2017.