Development of a Topological-Insulator-Based Quantum Resistance Standard

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***Abstract*—This paper describes the characterization of the quantum anomalous Hall (QAH) effect resistor with Chromium-doped Bismuth Antimony Telluride with the efforts in coupling directly to a programmable Josephson voltage standard (PJVS) at zero magnetic field. The precision measurement of the QAH resistance was performed under the presence of microwave signal biased to the PJVS. Understanding such effect will help to improve the experimental set-up for integrating multiple quantum electrical standards in a single system.**

***Index Terms*—electrical resistance measurement, measurement standards, precision measurements, topological insulators.**

I. INTRODUCTION

The ampere, the fundamental unit of electric current, can be indirectly realized through Ohm's law $\mathrm{A{=}V/\Omega}$. However, the practical realization of the ohm and volt, previously requiring separate cryostats for their differing operating conditions, has posed a challenge [1]. This obstacle is overcome by the quantum anomalous Hall (QAH) effect, which enables precise resistance measurements at zero magnetic field [2], [3]. This opens the door to combining multiple quantum standards within a single cryostat for simultaneous realization of the volt, ohm, and ampere.

This work presents a preliminary study on the behavior of QAH resistance when integrated with a programmable Josephson voltage standard (PJVS) in a dilution refrigerator (DR). We investigate the influence of microwave frequencies used to bias the PJVS and the noise introduced into the QAH resistor. Additionally, we report on the precision measurements and characterization of the device.

II. EXPERIMENTAL SET-UP

A. Integration of Quantum Electrical Standards

The QAH insulator sample was grown by molecular beam epitaxy on a semi-insulating GaAs (111)B substrate, with a 6-quintuple-layer (QL) Cr-doped $(\mathrm{Bi,Sb})_2\mathrm{Te}_3$ thin film. Details of the fabrication steps of the Hall bar are given in [4], which included photolithography, metal evaporation, etching, and atomic layer deposition. A top gate is used for tuning the Fermi level in the film. The longitudinal resistance R_{xx} was also measured as a function of gate voltage V_G to determine the optimal value in which R_{xx} is minimized. In our case, the QAH device works best when a 0 V is applied to V_G.

The QAH device is integrated with a PJVS in a single DR in attempt to realize the ampere and reduce the uncertainty of the current detection. The QAH device was located in the mixing chamber of the bridge, at the base temperature below $10\,\mathrm{mK}$, while the PJVS was mounted at the $4\,\mathrm{K}$ stage plate.

Prior to the characterization, the QAH device was pre-magnetized by applying a small magnetic field of $1\,\mathrm{T}$, then brought back to zero field.

B. Characterization of the QAH Device

The quantization of the device was verified by measuring its Hall bar resistance R_{xy} against a calibrated $100\,\Omega$ resistance standard, using a cryogenic current comparator bridge [2], [4]. The current applied in the QAH was in the range of $9\,\mathrm{nA}$ to $250\,\mathrm{nA}$. The values of these currents were chosen so that the voltage across the QAH resistance would match the quantized voltage of the PJVS. The precision measurements were performed at two conditions: when there was no radio frequency (RF) bias, and when a RF frequency was supplied to the PJVS.

III. RESULTS AND DISCUSSIONS

A. Heating via Microwave Leakage

The Hall bar resistance R_{xy} and the longitudinal resistance R_{xx} at each currents were measured and shown in Fig. 1. Without any biases to the PJVS , the relative deviation $\delta R_{xy} = (R_{xy} - \frac{h}{e^2})/\frac{h}{e^2}$ (shown as yellow, filled diamonds in Fig. 1a) was within $1\,\mu\Omega/\Omega$, the longitudinal resistance was smaller than a few hundreds $\mathrm{m}\Omega$.

Initially, without any shielding around the PJVS, when the microwave frequency f was turned on, noise of the R_{xy} measurement was increased and the temperature in the mixing chamber immediately heated up. The effect was also seen by the thermal sensor located near the sample space of the QAH device. It has been proven that the QAH quantization heavily depends on the temperature [5], therefore, as shown in Fig. 1, with the increase in current, R_{xy} and R_{xx} deviated significantly from the previous measurement when f was off.

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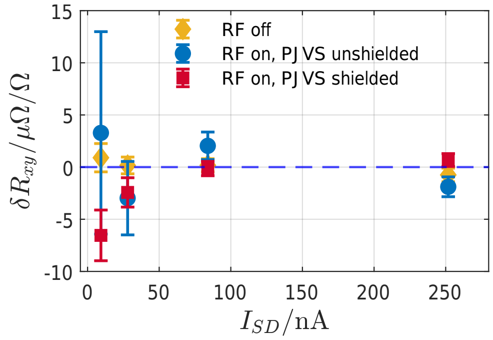
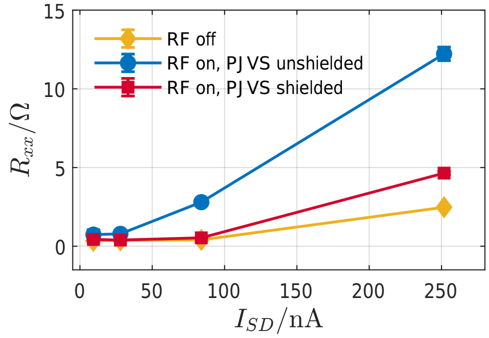


(a) Relative deviation of the Hall resistance of the QAH device from the nominal value.



(b) Longitudinal resistance of the QAH device, measured with a precised nanovoltmeter.

Fig. 1: The QAH was characterized with microwave bias turned off (marked with yellow diamonds), with microwave frequency $f = 9.701102806$ GHz, 0 dBm turned on, but PJVS was unshielded (blue circles), and with copper shield added around the PJVS (red squares). The error bars represent the combine uncertainty of the measurement ($k = 2$).

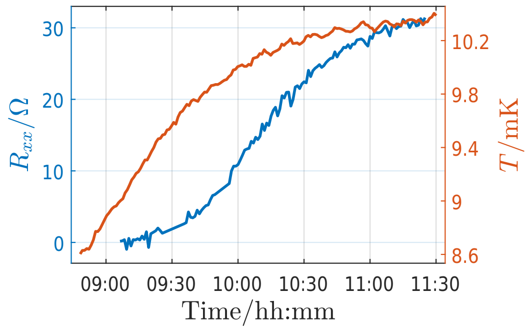


Fig. 2: Longitudinal resistance (blue line) and readings from a thermometer at the sample space (orange line) as a function of time after turning on the PJVS RF bias $f = 16$ GHz, 0 dBm.

Additionally, it was found that the heating effect also depended on the value of the bias frequency. Under some certain frequencies f, such as 9.701102806 GHz, 18.651341 GHz, and 15.3020182 GHz, the heating effect was minimal. Only several hours after changing to those the frequencies or turning off the RF completely, the QAH device would come to its equilibrium, as shown in Fig. 3. Hence, to avoid waiting such a long time, most of our experiments were done under the fixed optimal frequencies, where QAH quantization remained with few μΩ/Ω of the ideal value.

To reduce the effect of microwave leakage, the system was warmed up and a copper shield was added around the PJVS. The modification is shown to have substantial improvement to the results, as shown in the Fig. 1. Without any shielding, at the highest current of $250\,\text{nA}$, R_{xy} rose to some few parts in 10^{-6} and the discrepancy of R_{xx} was roughly 20 time higher. Meanwhile, the same measurements with shielding (red, filled squares) revealed a reduction in the deviation of R_{xx} and δR_{xy}. We believe that this behaviour is related to the cavity modes of the DR.

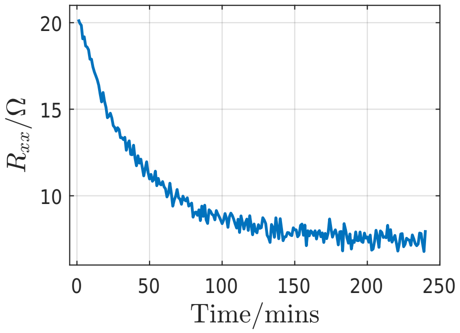


Fig. 3: Measurement of longitudinal resistance after changing the PJVS RF bias from $f = 16$ GHz to $f = 9.701102806$ GHz. $I_{SD} = 37\,\text{nA}$.

IV. CONCLUSION

For the goal of realization the quantum volt, ohm, and ampere from a single cryostat, we studied the QAH behaviour when it was integrated with a PJVS. It is found that, the microwave leakage has caused large deviations from the baseline of the Hall resistance of the QAH device. For future improvement, better radiative shielding and filtering should be implemented. A low-noise coaxial line set should also be implemented to reduce noise and to improve better electrical isolation. Finally, an improvement in topological material and wider Hall bar would help to increase the current range applied to the QAH device.

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