Assessment of Chromium-Doped Bismuth Antimony Telluride as a Quantized Anomalous Hall Resistance Standard

Linsey K. Rodenbach[*,£,⊥], Alireza R. Panna[*], Shamith U. Payagala[*], Ilan T. Rosen[*,£,⊥], Molly P. Andersen[£,⊥], Joseph A. Hagmann[*], Peng Zhang[‡], Lixuan Tai[‡], Kang L. Wang[‡], Dean G. Jarrett[*], Randolph E. Elmquist[*], Jason M. Underwood[*], David B. Newell[*], David Goldhaber-Gordon[£,⊥], and Albert F. Rigosi[*]

[*]National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, MD, 20899, USA
afr@nist.gov

[£]Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305, USA

[⊥]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

[‡]University of California, Los Angeles, California 90095, USA

***Abstract* —One major hurdle to making quantum resistance standards accessible to any basic research laboratory stems from the experimental requirement to generate strong magnetic fields for the quantum Hall effect to be exhibited in a metrologically robust way. However, with the synthesis of magnetically doped topological insulators (MTIs), which do not require a magnetic field to provide a quantized Hall resistance (QHR), a new avenue has been opened up. Here, measurement techniques and examinations of the quantum anomalous Hall effect (QAHE) are presented to prime the community for this potential paradigm shift, as efforts revolving around using MTIs for metrology continue to grow.**

***Index Terms* — quantized Hall resistance, quantum anomalous Hall effect, cryogenic current comparator, topological insulators.**

I. Introduction

Since 2017, epitaxial graphene has been the base material for the US national standard for resistance. Due to a relaxed magnetic field and temperature requirement, graphene-based devices enabled more user-friendly access to the quantum Hall effect and could more easily be deployed into US and global industries compared to GaAs-based devices [1,2]. A future avenue of research within electrical metrology is to remove the need for strong magnetic fields. New materials, like magnetically doped topological insulators (MTIs), offer access to the quantum anomalous Hall effect (QAHE), which in its ideal form, could become a future resistance standard needing only a small permanent magnet to activate a quantized resistance value [3]. Under ideal circumstances, thin-film MTI-based devices can host dissipationless conduction and a QHR, as experimentally observed in recent history [4]. These devices could operate at zero-field for measurements, making the dissemination of the ohm more economical and portable. Furthermore, one could assemble a single system with a Josephson voltage standard to realize the quantum ampere. Here we present results on precision measurements of the h/e^2 quantized plateau of a modulation doped MTI sample. Ultimately, MTI-based devices could be combined in a single system with Josephson voltage standards to obtain an alternative quantum current standard.

II. Preparation of TI devices and setup

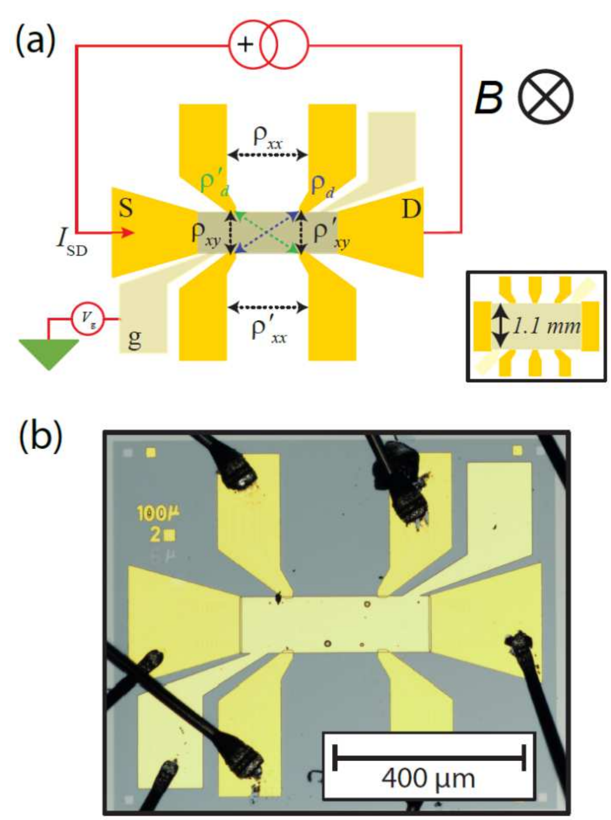

Fig. 1. (a) An illustration of the device design is shown, with the inset providing an alternate device design to enable more current to be injected. (b) An optical image of the device is provided.

The top and bottom layers of the modulation doped structure were Cr-rich $(Cr_{0.24}Bi_{0.22}Sb_{0.54})_2Te_3$. These single quintuple layers (QL) sandwiched 4 QLs of $(Cr_{0.12}Bi_{0.26}Sb_{0.62})_2Te_3$. The growth of the 6 QL of high-quality thin film took place on a semi-insulating GaAs (111)B substrate, with details provided in other work [5]. MTI-based devices were fabricated using direct-write optical photolithography. The electrical contact pads consisted of a 5 nm Ti adhesion layer and 100 nm Au. To implement a top gate, a dielectric layer of 1 nm of Al was uniformly deposited to act as a seed layer. This thin layer was oxidized before depositing about 40 nm of AlO_2. The top gate was deposited by evaporating 5 nm Ti and 85 nm Au.

Devices were mounted onto a 28-pin leadless chip carrier, which was tested to ensure that it was non-magnetic. An example diagram of the sample design and optical image are shown in Fig. 1 (a) and (b). It should be noted that there are two pairs of orthogonal electrical contacts for measuring the QAHE (labeled ρ_{xy} and ρ'_{xy}) and two pairs of contacts for measuring the longitudinal resistivity. The experiments were performed at a temperature of approximately 100 mK (determined by correlation of electron temperature to gate behavior in the presence of electrical noise).

B. Metrological Performance

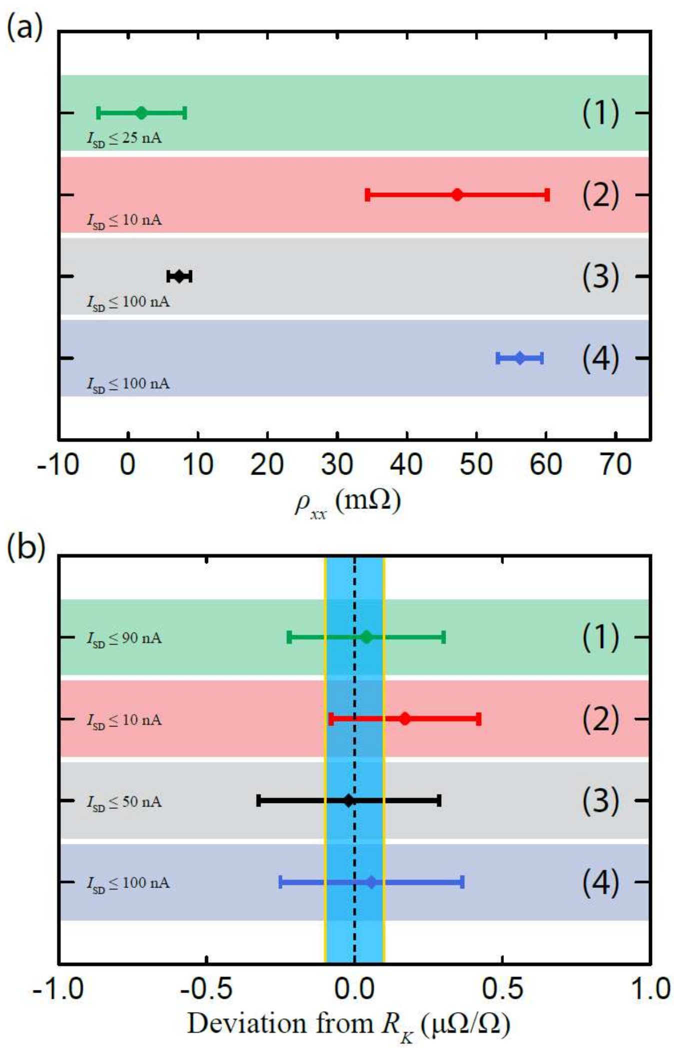

Fig. 2. A summary of the precision measurements of (a) ρ_{xx} and (b) the QAHE for the following MTI measurements are represented: 2018 NIST/Stanford (1 - green), PTB/UW (2 - red), this work's first device (3 - black), and the second device (4 - blue). The cyan region in (b) marks the boundary for data points going beneath one part in 10^7. All error bars represent combined standard uncertainties.

For precision measurements of the device, a 12-bit binary cryogenic current comparator (CCC) was used [6 ,7]. A CCC realizes an unknown resistance ratio R_1/R_2, from the inverse ratio of the dc bias currents I_1 and I_2. It consists of a superconducting toroidal screen which houses the superconducting windings N_1 and N_2. When a dc current is passed through these windings, due to the Meissner effect, a net current exists on the surface of the superconducting screen. The magnetic flux due to this net current imbalance is detected using a superconducting quantum interference device.

The assessment of the MTI-based devices is shown in Fig. 2. A summary of the precision measurements of ρ_{xx} and the QAHE are shown in (a) and (b), respectively, with data also including two summarizing points from previous studies [8, 9]. Applied currents vary and the following MTI measurements are represented: 2018 NIST/Stanford University (20 mK – green), Physikalisch-Technische Bundesanstalt / University of Würzburg (20 mK – red), this work's first device (100 mK – black), and the second device (100 mK – blue). The cyan region in (b) marks the boundary for data points going beneath one part in 10^7. All error bars represent combined standard uncertainties.

IV. Conclusion

This work presented results on precision measurements of the h/e^2 quantized plateau of $Cr_{0.12}(Bi_{0.26}Sb_{0.62})_2Te_3$. A future benefit to developing MTI-based devices includes the possibility for assembling a single system with a Josephson voltage standard to realize the quantum ampere. This material is based upon work supported by the Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division (Contract DE-AC02-76SF00515).

References

[1] A. F. Rigosi *et al.*, *Semicond. Sci. Technol.,* 34, 093004 (2019).
[2] A. F. Rigosi *et al.*, *Physica B Condens. Matter*, 582, 411971, 2020.
[3] Y. Okazaki *et al.*, *Nat. Phys*. 13, 1-5, 2021.
[4] X. Kou *et al.*, *Phys. Rev. Lett*. 113, 137201, 2014.
[5] L. Rodenbach *et al.*, *Phys. Rev. Appl.* 18, 034008, 2022.
[6] D. Drung *et al.*, *IEEE Trans. Instrum. Meas*. 62, 2820, 2013.
[7] T. Oe *et al.*, *IEEE Trans. Instrum. Meas*. 69, 3103-3108, 2019.
[8] E. J. Fox *et al.*, *Phys. Rev. B,* 98, 075145, 2018.
[9] M. Götz *et al.*, *Appl. Phys. Lett*. 112, 072102, 2018.