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Towards a Practical Resistance Standard

Quantum anomalous Hall effect with a permanent magnet defines a quantum resistance standard
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Recommended with a Commentary by Joe Checkelsky, Massachusetts Institute of Technology

The International System of Units (SI) has in recent decades undergone a quantum revolution. Previously reliant on physical artifacts for calibrations (*e.g.* the Pt-Ir alloy block known as the international prototype of the kilogram (IPK)), advances in atomic and quantum metrology have enabled the definition of standards in terms of fundamental constants. As such constants are available for all to measure (rather than a precision artifact which is kept under lock and key), this has opened the door to potentially deployable (and more broadly available) measurement standards. Among the condensed matter phenomena relevant to this effort, the quantum Hall (QH) effect has received significant recent attention for its ability to produce a quantum resistance standard. Originally envisaged as such at the discovery of Hall quantization $R_{yx} = iR_K \equiv ih/e^2$ by von Klitzing in 1980 [1], the (revised) von Klitzing constant $R_K = 25812.8074593045$ Ω was adopted as part of the SI in 2019 including in the definition of the kilogram [2].

Goals for deployable measurement standards based on the SI include establishing widespread, embedded calibrations for science and commerce as well as enabling high precision measurements proposed in fields ranging from nanoliter fluidics to quantum temperature sensing [3]. With the appreciation of the incredible precision apparently afforded by the QH effect, a question arises: what would make for a "good" platform for a QH-based resistance standard? From an electronic structure perspective, one might seek materials with large energy gaps between Landau levels to increase the thermal scale of the response. From a materials perspective, one might focus on robust, scalable systems that would enable device structures resistant to degradation. Further, materials and device structures together that support large measurement currents would aid in improving measurement resolution. From a deployment perspective, perhaps the most conspicuous consideration is the reduction of the cryogenic and superconducting magnet infrastructure needed to stabilize the QH response- the less complex the cryogenics and the smaller the externally applied magnetic field required the better (ideally none for both). Recent developments in quantum materials are now bringing such resistance standards towards more practical forms.

The conventional platforms for realizing the strict conditions for a resistance standard are semiconductor heterostructures based on GaAs/AlGaAs and require a typical magnetic field $\mu_0 H$ = 10 T. The quantum metrology community has identified graphene as a potential successor-owing to its linear electronic dispersion, graphene has a relatively large energy spacing between its lowest Landau levels that support an elevated energy scale. Furthermore, recent advances have demonstrated that resistance standard-level quantization can be achieved in CVD-grown graphene on SiC at fields down to $\mu_0 H$ = 3.5 T [4], enabling a scalable morphology. Parallel to this, there has been rapid developments in quantum anomalous Hall (QAH) systems [5], which in principle remove the requirement for external magnetic fields. Predicted [6] and discovered [7] in magnetically doped topological insulators (TIs), in these systems the time reversal symmetry breaking that drives the QH response is provided by the internal magnetization of the material. A natural expectation is that this might enable a path to a QAH resistance standard that obviates the need for a source of external field all together.

The highlighted work by Okazaki *et al.* takes two significant steps forward to a practical QAH standard. First, improving upon previous reports which already achieved impressive progress to a resistance standard [8], they report 10 parts per billion precision in a QAH material-comparable to those of commercial resistance calibration systems. This is achieved through the chemical optimization of the groundbreaking modulation doped architecture $Cr_{1-x}(Bi_{1-y}Sb_y)_{2-x}Te_3$ [9] which confines regions of high magnetic dopant to near the film surfaces. Further, building on their previous studies of the breakdown of the QAH effect [10], the measurement device is patterned as a relatively wide Hall bar to increase the measurement current, allowing μA scale excitations to be used. Second and perhaps more dramatically, they show that the system does not require a superconducting solenoid for the magnetic field, and achieve this precision via proximity to a nearby permanent magnet generating a local field $\mu_0 H \approx 0.2$ T. The authors show that the associated activation gap is nearly independent of the external field, connecting to the expectation of an exchange-driven effect. In this case the role of the field is to align the internal magnetic domains of the system upon cooling to form a uniform Chern gap rather than generate Landau levels from electronic orbital motion.

Not only does the removal of a large superconducting magnet dramatically simplify the experimental setup for a resistance standard, it has the potential to enable direct integration with, for example, Josephson junction voltage standards and single-electron transistor current standards in the pursuit of the "quantum metrology triangle" that could enable self-calibrating electronics [11]. However, despite the significant simplification of the magnetic field source, extreme cryogenic conditions are still required for even these finely engineered magnetically doped TIs. Given that the ferromagnetic order in these structures occurs at temperatures more than an order of magnitude larger than the onset of quantization, there is still significant room for elevating the operating temperature.

It is interesting to consider the potential implications for the other (chemical substitution-free) systems in which the QAH has recently been reported, such as $MnBi_2Te_4$ [12], twisted bilayer graphene [13], and $MoTe_2/WSe_2$ heterobilayers [14]. While these new platforms have not yet reached study as resistance standards, they represent distinct pathways to realizing a QAH platform. Though all still require liquid Helium temperatures for operation, the micron-scale twisted bilayer graphene devices, for example, support an activation gap which significantly exceeds their Curie temperature and potentially enable electrical current control of magnetization, suggesting a distinct materials starting point for this challenge. Finally, as the magnetic field scale for the "conventional" QH effect is reduced, it may be that materials such as GaAs or single layer graphene also approach resistance-standard levels with permanent magnets (see *e.g.* [15]). All this broad and rapid progress has opened the gates for a quantum materials race to enable new practical standards.

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