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# QuAHMET: Quantum anomalous Hall effect materials and devices for metrology

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ABSTRACT

QuAHMET — Quantum anomalous Hall effect materials and devices for metrology is a Joint Research Project of the European Metrology Partnership research funding programme. The project focus is the traceable measurement and characterisation of quantum anomalous Hall effect (QAHE) materials as devices, enabling them as the foundation for the future generation of primary realisations of the resistance unit, the ohm (Ω).

## 1. Introduction

The Quantum Hall effect (QHE) is the foundation for the realization of the SI unit of electrical resistance, the ohm (Ω) [1].

QHE devices typically employed in National Metrology Institutes (NMIs) are based on the two-dimensional electron gas (2DEG) confined at the interface of a gallium arsenide heterostructure. These devices, for proper quantization, impose extreme conditions (<1.5 K temperature, >10 T magnetic field), which are challenging and expensive to achieve in a laboratory, and therefore making their universal adoption challenging. In addition, they sustain currents up only to a few tens of μA.

The advent of graphene-based QHE devices [2] has significantly relaxed the temperature and magnetic field requirements. The current working temperature is 4.2 K, and the field is limited to 4–5 T. Current research and development activity on epitaxial graphene, however, promises only incremental improvements. In particular, it is not expected to address the need for operation at smaller magnetic fields, higher critical currents, and ease of fabrication into large-area device geometries.

The discovery of topological quantum materials [3,4] circumvents the necessity for high magnetic fields and strict control of carrier mobilities. These materials can realise the so-called Quantum Anomalous Hall effect (QAHE) [5] at small [6] or zero [7] magnetic field independently of carrier mobilities, which could lead to higher critical currents. Additionally, the devices can potentially be fabricated into large area quantum Hall device geometries, making them attractive for metrologists as future primary resistance standards.

Further improvements in the operating conditions of primary resistance standards will usher in the development of the 'quantum electrical metrology toolbox', the combination of electrical standards of voltage, resistance and current, possibly operating both in the dc and the ac regime, for a near-universal adoption of quantum electrical SI standards at NMIs, industrial end users, and calibration laboratories.

***QuAHMET - Quantum anomalous Hall effect materials and devices for metrology*** is a Joint Research Project of the European Partnership on Metrology [8] research funding programme. European Partnerships are a key implementation tool of the European Commission's *Horizon Europe*.

The QuAHMET project focus is on the traceable measurement and characterisation of quantum anomalous Hall effect (QAHE) materials as devices and primary resistance standard candidates. The project is exploring, understanding, and implementing a scientifically grounded methodology for developing metrology grade QAHE devices with relatively larger geometries that achieve resistance quantization at zero magnetic field, above 1 K temperature and with currents greater than 1 μA. These implementations will accelerate the development of the aforementioned quantum electrical metrology toolbox for universal adoption of quantum electrical SI standards.

The current requirements for extreme experimental conditions and intrinsic material/device limitations of QAHE make accurate measurements non-trivial. To address this, NMIs are developing and applying both novel and consolidated measurement methods for metrological assessment of QAHE devices to achieve both best and medium uncertainty ranges, opening the possibility of knowledge transfer beyond NMIs to research laboratories.

Realising a 'quantum electrical metrology toolbox' with a zero-field quantum Hall resistance together with a Josephson voltage standard being integrated in a single cryostat would be an unprecedented achievement within quantum electrical metrology. Via the fan-out effect in the pyramid-like structure of traceability chains from the NMIs to millions of measurements and calibrations, European calibration services and industry will benefit from such "resistance-standard-on-the-workshop-floor". This will improve the growth and investigate the electronic, structural, magnetic, and magneto-electronic properties of high structural quality TIs materials optimised for the QAHE to develop and carry out their detailed metrological assessment. In prospective, this will provide a range of new measurement capabilities at NMIs of direct relevance to the scientific and the industrial communities.

## 2. Project objectives

The specific objectives of the QuAHMET project are:

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1. To improve the growth of magnetically doped topological insulator (TI), (e.g., $Bi_2Te_3$ and $Sb_2Te_3$) thin film samples by molecular beam epitaxy on closely lattice matched substrates. Furthermore, to explore the effects of anisotropic magnetic insulator layers interfaced with TIs and produce high structural quality materials with properties optimised for the QAHE.
2. To investigate the bulk electronic, structural, magnetic, and magneto-electronic properties of the above samples by using QAHE devices under various temperatures (from below 50 mK up to 300 K), currents (from below 100 nA to over 1 μA), and applied magnetic fields (from 0 to 10 T) for different growth conditions. In addition, to investigate the limitations of QAHE, i.e., low critical temperatures and currents when working on precision growth-control of interfaces.
3. To investigate QAHE thin films and devices produced in Objective 1 by surface-sensitive scanning probes, magnetometry techniques at low temperatures, and to characterise the magnetic and structural properties with high lateral resolution using X-ray and neutron investigations.
4. To develop and carry out detailed metrological assessments of optimised QAHE devices, both at sub-Kelvin and above 1 K temperatures, aiming at QAHE resistance quantization accuracy between 1 and 10 ppm, above 1 K, at currents above 1 μA and at low-to-zero applied magnetic field. In addition, to write a good practice guide on the use of QAHE devices for resistance metrology.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by standards developing organisations (BIPM), end users interested in applications, such as spintronics and topological quantum computing and advance the research and progress in the field of TIs.

## 3. The project implementation

The project is structured in five workpackages:
WP1: Thin film growth, quality optimization and device fabrication.
WP2: Property characterization of QAHE material films and devices.
WP3: QAHE precision metrology.
WP4: Creating impact.
WP5: Management and coordination
which interact throughout the project as shown in the diagram of Fig. 1.

The consortium includes 14 partners, gathering 7 leading European National Metrology Institutes (NMI), a Japanese NMI for metrology, complemented by 6 globally recognized institutes from academia and applied research (see Fig. 2). A detailed list of the partners is shown in Table 1. In the area of producing QAHE materials and devices the partners JMU and KU have partly redundant roles to ensure timely delivery of the project.

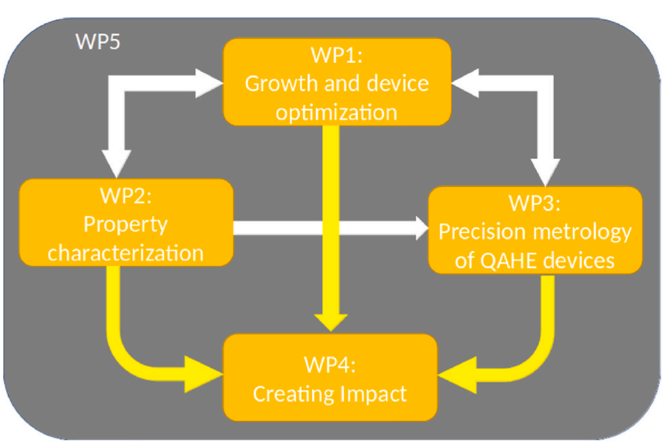


**Fig. 1.** Pictorial representation of the interaction between the five workpackages of the project, four technical and one (the grey background in the picture) devoted to project management.

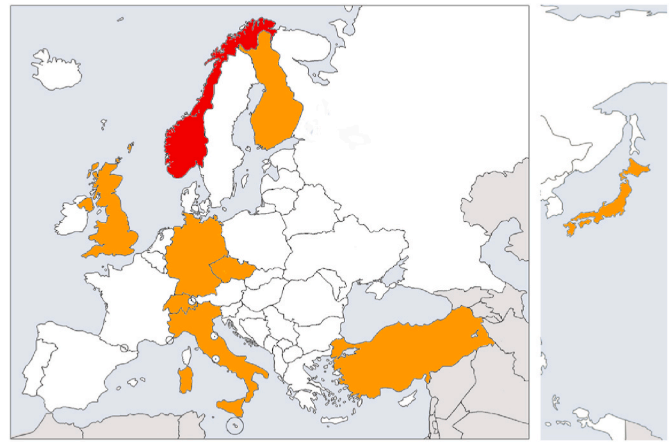

**Fig. 2.** The countries involved in the QuAHMET project.

## 4. Progress

The project is still in its infancy, but it is boosted by the long-term research investments and activities of the partners.

### 4.1. Device fabrication and characterisation

The device materials are grown by molecular beam epitaxy (MBE) using high resolution x-ray diffraction (HRXRD) for crystal phase purity and structure, reflection high electron energy diffraction (RHEED) for in situ growth control, x-ray photoelectron spectroscopy (XPS) for valence states and stoichiometry of especially the dopant ions. Characterisation techniques include also Raman spectroscopy, resistivity, superconducting quantum interference device (SQUID) magnetometry, scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDX), high resolution transmission electron microscopy (HRTEM), a multitude of surface sensitive scanning probe microscopy (SPM) techniques at low temperatures for imaging nanoscale electronic/magnetic inhomogeneities and edge/surface/bulk states, X-ray reflectometry (XRR).

**Table 1**
List of project participants.

| no | Short Name | Organisation legal full name | Country |
|---|---|---|---|
| 1 | JV | Justervesenet | Norway |
| 2 | CMI | Cesky Metrologicky Institut | Czechia |
| 3 | INRIM | Istituto Nazionale di Ricerca Metrologica | Italy |
| 4 | PTB | Physikalisch-Technische Bundesanstalt | Germany |
| 5 | TUBITAK | Turkiye Bilimsel ve Teknolojik Arastirma Kurumu | Türkiye |
| 6 | JMU | Julius-Maximilians-Universität Würzburg | Germany |
| 7 | Koc | Koç Üniversitesi | Türkiye |
| 8 | TAU | Tampereen korkeakoulusäätiö sr | Finland |
| 9 | UNILE | Università del Salento | Italy |
| 10 | AIST | National Institute of Advanced Industrial Science and Technology | Japan |
| 11 | METAS | Eidgenössisches Institut für Metrologie METAS | Switzerland |
| 12 | NPL | NPL Management Limited | United Kingdom |
| 13 | UNIBAS | Univsersitat Basel | Switzerland |
| 14 | UOXF | The Chancellor, Masters and Scholars of the University of Oxford | United Kingdom |

Different types of quantum anomalous Hall effect material systems are being considered:

- Highest quality Vanadium-doped $(Bi,Sb)_2Te_3$ (also called VBST) ferromagnetically doped TIs (FMTIs) on closely lattice matched substrates, such as InP(111) and Si(111);
- Kagome magnets, which intrinsically combine topology and magnetism, and are considered excellent platforms [9]. In particular, intrinsic (ferro-, antiferro-, ferri-) magnetic Kagome films and Kagome superconducting films. Kagome–Ferromagnets: $A_x(Sn, Ge)_y$ (A = Fe or Co; x:y = 3:2 or 1:1), Kagome–Ferrimagnet: $RMn_6Sn_6$ (R = Gd, Ho), Kagome–Antiferromagnet: $Mn_3Sn$ and $Mn_3Ge$, Kagome–Superconductor: $AV_3Sb_5$ (A = K, Rb, Cs);
- undoped and rare earth $(Bi,Sb)_2Te_3$ on magnetic insulators (e.g. YIG, TmIG).

The devices will then be fabricated using standard lithography, and packaged by wire bonding in holders suitable for cryogenic electrical measurements.

An example of magnetic characterization of the samples being produced is shown in Fig. 3, which gives the magnetic moment temperature dependency for different intensities of the applied magnetic field on an epitaxial Cr-Doped $(Bi_{1-x}Sb_x)_2Te_3$ sample. The outcome is consistent with the remnant moment data in that a transition at about 120 K is visible in the inset. The high field peak that appears at around 50 K shows that surface magnetism is becoming stronger at low temperatures. The coercive field decreases with temperature, as expected.

An example of the electrical characterisation of a topological insulator device is shown in Fig. 4. A Hall bar device, fabricated by the university of Würzburg from the vanadium-doped topological insulator BiSbTe, was measured at the temperatur $T$ = 34 mK in a dilution refrigerator. A current $I = 5$ nA is applied and the longitudinal $V_{\mathrm{long}}$ and transverse $V_{\mathrm{Hall}}$ voltages are recorded as a function of the applied magnetic field $H$; to improve signal to noise ratio, a lock-in technique was employed. A gate voltage was applied to a top gate above the device, to tune the chemical potential to the centre of the energy gap in the bulk of the device. The typical fingerprint of the quantum anomalous Hall effect is observed: the Hall resistance $R_{\mathrm{Hall}} = V_{\mathrm{Hall}}/I$ is quantized to the von Klitzing constant value $R_K = h/e^2$, where $h$ is the Planck constant and $e$ the elementary charge. Correspondingly, the longitudinal resistance $R_{\mathrm{long}} = V_{\mathrm{long}}/I$ vanishes.

$R_{\mathrm{Hall}}$ depends on the history of the applied magnetic field $H$ and follows an hysteresis loop path. The quantization at zero magnetic field [10] is the striking property that opens the multiplicity of applications of QAHE in metrology.

### 4.2. Primary metrology

Precision measurements of QAHE devices involve the setting and verification of the quantization conditions, and the high-accuracy comparison of the quantized resistance value versus a maintained resistance scale. The quantization conditions, with base temperatures in the 100 mK - 1 K range, can be achieved with either liquid helium or dry cryostats, equipped with multistage cooling systems (e.g., dilution refrigeration). Fig. 5 shows one of the cryostats that will be employed in the project, presently under testing.

Ultimate measurement accuracy can be achieved with cryogenic current comparator (CCC) bridges, where the resistance ratio is compared with the turns ratio of a dc superconducting transformer, using a superconducting-quantum-interference-device (SQUID) as a magnetic flux null detector.

Despite the extreme sensitivity of the SQUID detector, performing a resistance ratio measurement with current excitations in the nA range is extremely challenging. Nevertheless, it is possible to achieve a measurement uncertainty below one part per million [10]. The partners are working together for further improvements in the measurement accuracy [11].

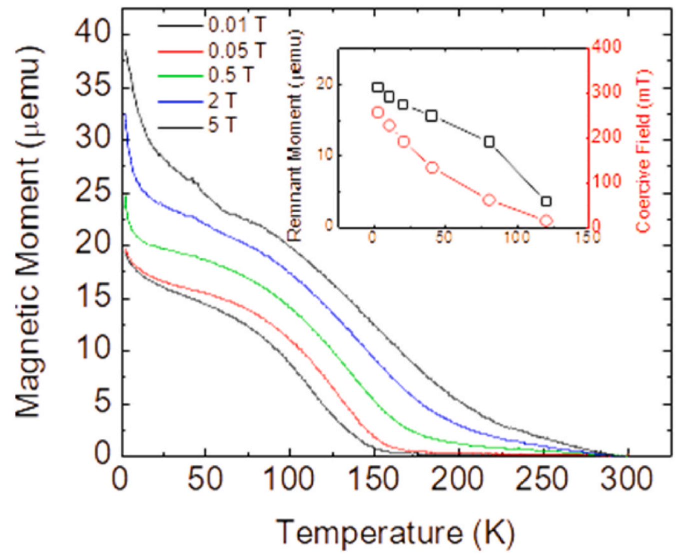


**Fig. 3.** (main plot) the magnetic moment temperature dependency, for different intensities of the applied magnetic field, on an epitaxial Cr-Doped $(Bi_{1-x}Sb_x)_2Te_3$ sample. (inset) the remnant magnetic moment and the coercive field dependence over temperature.

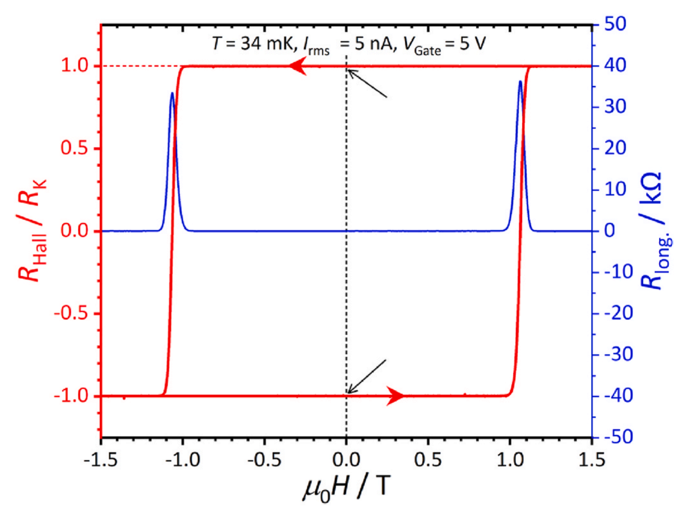


**Fig. 4.** The Hall resistance (red, left axis) and the longitudinal resistance $R_{\mathrm{long.}}$ (blue, right axis) versus the applied magnetic field $H$.

The aim of achieving an universal adoption of the QAHE as a resistance standard cannot rely only on CCCs, which are expensive instruments in need of a separate cryogenic environment. Therefore, the project is also pursuing the development of resistance ratio measurement setups that can operate at room temperature and achieve an uncertainty in the 10 ppm range or below, based on commercial instrumentation and easily duplicable by the partners and the project stakeholders [12].

## 5. Connect to the project!

The project is committed to open science practices that will be implemented as integral parts of the methodology. Research institutions, calibration laboratories and instrument manufacturers are welcome to connect to the project as stakeholders. The project will communicate to the interested parties through.

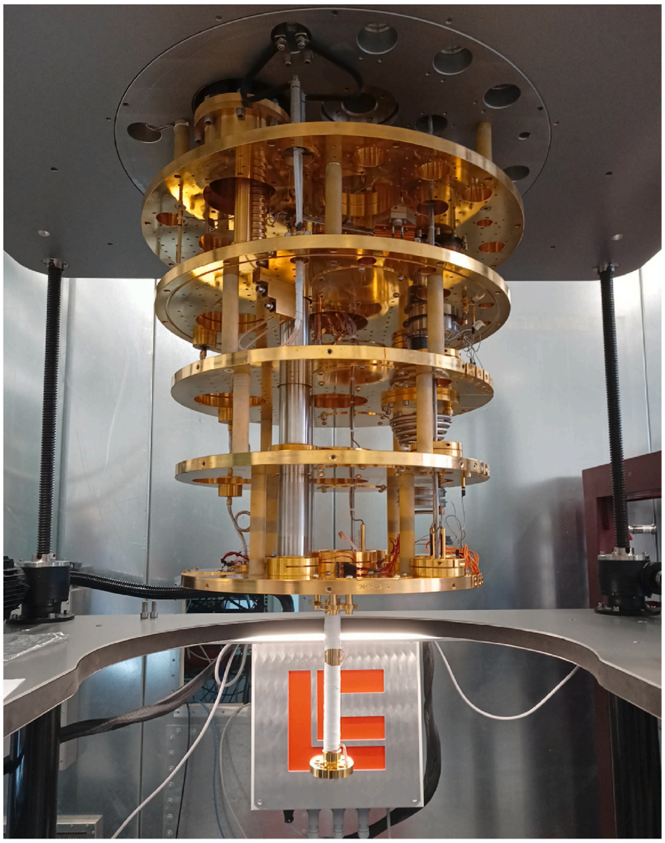


**Fig. 5.** One of the cryostats employed in the project, which is presently being equipped for measurements on QAHE devices. It is a 2 W pulsed cryocooler equipped with a dilution refrigerator, with a base temperature of 15 mK and a cooling power of 500 μW at 120 mK, and a 9 T superconducting magnet. The cold finger at the bottom supports a shielded sample holder which is positioned in the center of the magnet.

### Its LinkedIn group

www.linkedin.com/groups/8824119/

### A YouTube channel

www.youtube.com/channel/UCaHuyb8YzrjPnLUz7nSiauA.

Its **periodic Newsletter**, whose first issue is expected in Summer 2024.

You can connect to the project by sending an email to the Impact workpackage leader, Martina Marzano (m.marzano@inrim.it).

### Its website

sites.google.com/inrim.it/quahmet/home.


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