Magneto-transport in inverted HgTe quantum wells
Ivan Yahiuk, Sergey S. Krishtopenko, Grzegorz Grabecki, Benoit Jouault, Christophe Consejo, Wilfried Desrat, Magdalena Majewicz, Alexander M. Kadykov, Kirill E. Spirin, Vladimir I. Gavrilenko, et al.

To cite this version:
Ivan Yahiuk, Sergey S. Krishtopenko, Grzegorz Grabecki, Benoit Jouault, Christophe Consejo, et al.. Magneto-transport in inverted HgTe quantum wells. Npj Quantum Materials, Nature publishing, 2019, 4, pp.13. 10.1038/s41535-019-0154-3. hal-02302388

HAL Id: hal-02302388
https://hal.archives-ouvertes.fr/hal-02302388
Submitted on 1 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Magneto-transport in inverted HgTe quantum wells

Ivan Yahniuk, Sergey S. Krishtopenko, Grzegorz Grabek, Benoit Jouault, Christophe Consjeo, Wilfried Desrat, Magdalena Majewicz, Alexander M. Kadykov, Kirill E. Spirin, Vladimir I. Mikhailov, Nikolay N. Mikhailov, Sergey A. Dvoretsky, Dmytro B. But, Frederic Teppe, Jerzy Wróbel, Grzegorz Cywiński, Sławomir Kret, Tomasz Dietl and Wojciech Knap

HgTe quantum wells (QWs) are two-dimensional semiconductor systems that change their properties at the critical thickness $d_c$, corresponding to the band inversion and topological phase transition. The motivation of this work was to study magneto-transport properties of HgTe QWs with thickness approaching $d_c$, and examine them as potential candidates for quantum Hall effect (QHE) resistance standards. We show that in the case of $d > d_c$ (inverted QWs), the quantization is influenced by coexistence of topological helical edge states and QHE chiral states. However, at $d = d_c$, where QW states exhibit a graphene-like band structure, an accurate Hall resistance quantization in low magnetic fields ($B \lesssim 1 T$) and at relatively high temperatures ($T \gtrsim 1.3 K$) may be achieved. We observe wider and more robust quantized QHE plateaus for holes, which suggests—in accordance with the “charge reservoir” model—a pinning of the Fermi level in the valence band region. Our analysis exhibits advantages and drawbacks of HgTe QWs for quantum metrology applications, as compared to graphene and GaAs counterparts.

ARTICLE

INTRODUCTION

Mercury cadmium telluride (Hg$_x$CdxTe) zinc-blende compounds are an example of rare semiconductor materials that form alloys over the whole composition range $x$ while keeping the same crystal structure and the virtually unaltered lattice parameters. Accordingly, it is possible to tune the band structure by changing $x$ and grow bulk films, two-dimensional (2D) quantum wells (QWs) or superlattices without strain-related material degradation. In this sense, Hg$_{1-x}$Cd$_x$Te crystals are similar to the well-known Ga$_{1-x}$Al$_x$As semiconductors, but show a much larger bandgap tunability, with band gaps ranging from $E_g \approx 1.6$ eV for CdTe to the inverted band ordering, with $E_g \approx 0.3$ eV for HgTe at 4.2 K. This peculiar aspect of Hg$_{1-x}$Cd$_x$Te allows to reach $E_g = 0 \text{ eV}$ and the conditions for observation of 3D Dirac carriers with massless Dirac-like linear dispersion and with high values of room- and low-temperature electron mobilities reaching $3.5 \times 10^4$ and $2 \times 10^6 \text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$, respectively. Moreover, since it is possible to adjust the bandgap below 100 meV, Hg$_{1-x}$CdxTe-based systems are broadly employed in infrared and terahertz detectors, cameras, and lasers.

Recent technological advances in molecular beam epitaxy (MBE) of Hg$_{1-x}$CdxTe-based quantum structures have opened new and striking possibilities. In particular, HgTe/(Cd,Hg)Te QWs have allowed the demonstration of the existence of various topological phases in condensed matter. By changing the QW widths, the barrier alloy composition and the number of coupled QWs, it has been possible to demonstrate 2D topological insulators with 1D edge conducting channels as well as structures with band dispersions similar to single layer bilayer graphene. Taking into account that Hg$_{1-x}$CdxTe-based quantum structures have already broad commercial applications in night/thermal vision cameras and photonics, and that the MBE-grown HgTe QWs show a potential as a new generation of infrared and THz detectors, it is of interest determining structure layouts and experimental conditions under which the magnitude of Hall resistance can assume accurately quantized values, and to consider a potential of this material system for the quantum Hall effect (QHE) resistance standards.

QHE resistance standards make use of the accurate QHE quantization of the Hall resistance given by $\rho_{xy} = h/ie^2$, where $i$ is an integer, and $h$ and $e$ are the Planck constant and the electron charge, respectively. Since their discovery, QHE standards have become a highly important tool in quantum metrology and are widely used in many national/international standardization institutions today. Currently, many materials are used for QHE standards. Despite differences in the material band structure, the sample imperfections and the geometry, unbelievably precise and wide Hall resistance plateaus are observed, independent of the host material, with a precision at the level going up to a few parts in $10^{10}$ (refs 21–23). However, all used resistance standards operate at stringent experimental conditions: high magnetic fields $B$ (requiring the use of superconducting coils) or extremely low temperatures $T$ (requiring often the use of dilution $^3$He refrigerators). For example, typically, $B = 10 T$ and $T = 1.5 K$ for the GaAs-based standards. Recently, using the anomalous QHE resistance of a ferromagnetic topological insulator, the feasibility of QHE resistance standards without high magnetic fields was demonstrated.

Published in partnership with Nanjing University
One has to mention, however, that the data in Fig. 1 concerns only magnetic field and temperature magnitudes (cryomagnetic conditions) of QHE standards.\textsuperscript{39-41} Of course, in practical applications, other factors have to be taken into consideration, such as a minimum time of the measurement to achieve the required accuracy (determined by signal to noise ratio that improves with the magnitude of breakdown current), the mastering and reproducibility of processing, metallization and packaging, long term stability of the device, and its cost.\textsuperscript{50-22,39-41}

The main objective of this work is study magnetotransport properties of HgTe/(Cd,Hg)Te QWs in their different topological phases, determine importance of topological helical edge conduction and to examine different QWs from the point of view of their potential applications for QHE resistance standards. Our work is motivated by possibility of growth of QWs with (i) graphene-like band structure (large Landau Level splitting) and (ii) very high mobility carriers as well as (iii) developed device fabrication techniques, ensuring nowadays successful.

In this work, we experimentally and theoretically demonstrate that HgTe/(Cd,Hg)Te QWs with the thicknesses close to the critical value $d_c$ and trivial band order, eliminating coexistence of conducting topological helical edge states together with QHE chiral states, allows reaching very favorable cryomagnetic conditions for the QHE resistance standards operation: low enough magnetic fields enabling use of permanent magnets ($B \lesssim 1.4$ T) simultaneously with liquid $^4$He coolers (temperatures of $T \lesssim 1.3$ K)—reaching the cian region in Fig. 1.

**RESULTS**

Investigated structures

Quantum structures were grown by MBE on GaAs (013) substrates.\textsuperscript{17} Three samples S1, S2, and S3, containing HgTe QWs with the thicknesses and barrier compositions of 7.1 nm, 8.0 nm, HgTe/Cd$_{0.27}$Hg$_{0.73}$Te, and 6.5 nm, HgTe/Cd$_{0.25}$Hg$_{0.75}$Te, respectively, have been studied. Measurements were performed on lithographically defined Hall bars with the dimensions of $L \times W = 80 \times 20 \mu$m$^2$ and $L \times W = 40 \times 20 \mu$m$^2$ (samples S1 and S2, respectively) and $L \times W = 650 \times 50 \mu$m$^2$ (sample S3). In addition, samples S2 and S3 had a top gate electrode allowing for carrier density control.\textsuperscript{42}

Figure 2a, b shows the layer sequence scheme and high-resolution electron microscopy (HREM) images of the cross section of sample S1. A perfect alignment of the successive atomic layers with the well-defined HgTe QW can be seen in Fig. 2b. Such high growth quality is crucial for obtaining the appropriate carrier mobility of HgTe QWs for QHE standards and can be reached only by the MBE growth technique.

Contribution of the TI states in QHE measurements

Most of the magnetotransport experiments were performed using the BT superconducting magnet system and standard lock-in measurement techniques. High-precision resistance measurements were performed using an HP3458A multimeter. The longitudinal and transverse resistances $\rho_{xx}(B)$ and $\rho_{xy}(B)$ for sample S1 are shown in Fig. 3a. The data correspond to $T = 1.7$ K, the hole concentration of $3.4 \times 10^{19}$ cm$^{-2}$ and mobility of $14.9$ m$^2$ V$^{-1}$ s$^{-1}$. A well-developed QHE plateau is visible already at $B = 0.7$ T. However, the $\rho_{xy}$ quantization is not exact, and $\rho_{xx}$ does not go to zero.

In the search for the origin of this parasitic $\rho_{xx}$ conductivity, we consider the possibility of conduction through topological insulator 1D edge channels, as shown schematically in the inset of Fig. 3b.

We calculate the band structure and Landau Levels (LLs) fan charts for samples S1–S3 using the eight-band $k \cdot p$ Hamiltonian,\textsuperscript{43} including the $\Gamma_m$, $\Gamma_6$, and $\Gamma_7$ bands of bulk materials and strain

![Fig. 1](image-url)
effects due to lattice constant mismatch, with the parameters confirmed by our earlier investigations.\textsuperscript{44,45} According to the calculation results presented in Fig. 3, sample S\textsubscript{1} has an inverted band structure up to the critical magnetic field $B_c \approx 4$ T, at which a crossing of the highest LL from the valence band with the lowest LL from the conduction band occurs.\textsuperscript{46,47} Interestingly, $\rho_{xx}$ tends to be zero precisely when the magnetic field approaches $B_c \approx 4$ T (see Fig. 3b). This suggests that the existence of the inverted band structure and the related topological gap are detrimental to good quantization. It is possible that the combination of both counter-propagating topological edge states and disorder promotes backscattering beyond the expected topological gap. Supporting this view results proving that the 1D edge conducting channels are indeed active even when the Fermi level is located beyond the topological gap have been obtained in the previous work.\textsuperscript{48}

To further explore conduction through the edge channels, we have investigated sample S\textsubscript{2}, which was equipped with a top gate controlling the carrier type and density. This sample also has an inverted band structure similar to sample S\textsubscript{1}, but with a slightly larger negative energy gap. Well-developed quantum resistance plateaus $\rho_{xy} = \pm e^2/h$ were observed at magnetic fields starting from above $\approx 2$ T for electrons and above $\approx 5.5$ T for the holes, as illustrated in Fig. 4a and the 2D map in Fig. 4b. The edge state conduction is revealed by the
results of the nonlocal resistance measurements, as shown in the 3D plot in Fig. 4b. Configuration of the nonlocal measurements presented in supplementary materials (see Fig. S1). The value of $R_{\text{NL}}$ is plotted on the logarithmic scale to better visualize the residual edge conducting channels extending up to the QHE regions. As shown in Fig. 4 the resistance becomes very large when the Fermi level lies in the topological gap and decreases for magnetic fields higher than the critical value ($B_c = 6$ T for sample S2). As can be seen, in spite of the nonlocal resistance has its maximum for the Fermi level close to the charge neutrality point, the nonlocality still persists for the Fermi levels located in the band—far from the gap, extending to the QHE regions, as shown by the 2D map plotted above the 3D nonlocal resistance graph (Fig. 4b).

The existence of the critical field $B_c$ separating topological and non-topological phases, is a specific feature of charge transport in the inverted bandgap region of HgTe quantum wells. This feature has recently been explored to trace topological phase transition as a function of temperature.  

### 6.5 nm QW in a magnetic field

Based on results presented above, we conclude that HgTe QWs with the smallest possible $B_c$ should be engineered to decrease or avoid topological edge states perturbing the precision of the QHE. Figure 5 shows the band structure of sample S3. This sample has the smallest gap, and the smallest critical magnetic field of the three investigated samples, $B_c = 1.7$ T. The magnetoresistance data for sample S3 are shown in Fig. 5. On the electron side ($V_g = -1.2$ V, $\mu = 5$ m$^2$ V$^{-1}$ s$^{-1}$, panel c), the $\nu = 1$ plateau is observed above 1.5 T. The longitudinal resistance $R_{xx}$ is $< 0.1$ $\Omega$ in $B = 2.5$ T, and $R_{xx} = 25.807 \pm 7$ $\Omega$, yielding the relative accuracy in the range of $\Delta R_y/R_y \approx (-2 \pm 3) \times 10^{-4}$.

On the hole side ($V_g = -2.5$ V, $\mu = 20$ m$^2$ V$^{-1}$ s$^{-1}$, panel d), the QHE is observed at a very low magnetic field $B \approx 0.5$ T. However, there is a small residual contribution $\rho_{xx} \approx 20$ $\Omega$ at this field, which we attribute to the counter-propagating topological edge states. Indeed, this residual resistivity decreases with magnetic field and is finally strongly suppressed, dropping to $< 0.1$ $\Omega$ around $B = 2$ T. Band structure calculations show that (similarly to the S1 and S2 samples) this field corresponds to the crossing of the conduction and valence band levels as well, signifying the transition from the inverted to the trivial band structure ($B \approx 1.7$ T, Fig. 5b).

In Fig. 5c, d, we show $\rho_{xx}(B)$ and $\rho_{xy}(B)$ for HgTe QWs with similar electron and hole densities adjusted by the gate voltage, whereas Fig. 5e presents a contour plot of $\sigma_{xy}$ over a wide field and carrier density range. One can clearly see that the quantized value corresponding to $\nu = 1$ appears at a lower magnetic field for holes than in the n-type case. Also the QHE plateau is wider for holes. These facts can be attributed to the Fermi level pinning in the valence band region by a charge reservoir located either at QW or oxide interfaces. In fact, the charge transfer between interface states and the conducting channel is often considered as a complementary or a competing process to the well-known localization mechanism accounting for a non-zero width of QHE plateaus. Such reservoir-related effects have also been observed in G/SiC, in which a surprisingly long plateau for $\nu = 2$ is assigned to the presence of interfacial charges residing between graphene and the SiC substrate. However, in the case of the QHE of holes in HgTe QWs, it is still not clear what is the role played by side maxima in the energy dispersion of the valence subband depicted in Fig. 5a. It is worth stressing that independently of underlining mechanism, our experimental observations show that for metrology applications slightly p-type doped non-topological HgTe QW’s should be used.
Summing all the $R_H$ values collected between $1.8 < B < 3$ T at $I_{dc} = \pm 1 \mu A$, we obtain $\Delta R_H/R_H \approx (3 \pm 30) \times 10^{-5}$. To further increase the overall precision, it would be mandatory to fabricate the QWs with smaller width (non-inverted band structure). Also sample geometry and contacts technology should be improved to maximize the magnitude of the breakdown current (see Discussion below).

Strain engineering for metrology applications
The results presented above show that good quantization precision at fields close to 0.5 T can be obtained with material engineering (slightly narrower QWs with the non-inverted band structure, $B_c = 0$ T). Further improvements in the QHE metrological conditions, i.e., lowering the operating magnetic field and increasing the temperature can be obtained in the QWs with higher Fermi velocity $v_F$. This velocity is determined by the slope of the linear energy dispersion, and its rise increases the energy spacing between the LLs. Recently, it has been experimentally demonstrated that the use of CdTe-Cd$_{0.5}$Zn$_{0.5}$Te strained-layer superlattices on GaAs as virtual substrates with an adjustable lattice constant allows effective control of the biaxial strain in the superlattices on GaAs as virtual substrates with an adjustable lattice constant allows effective control of the biaxial strain in the structure, $B_c = 0$ T). Further improvements in the QHE metrological conditions, i.e., lowering the operating magnetic field and increasing the temperature can be obtained in the QWs with higher Fermi velocity $v_F$. This velocity is determined by the slope of the linear energy dispersion, and its rise increases the energy spacing between the LLs. Recently, it has been experimentally demonstrated that the use of CdTe-Cd$_{0.5}$Zn$_{0.5}$Te strained-layer superlattices on GaAs as virtual substrates with an adjustable lattice constant allows effective control of the biaxial strain in the HgTe QWs from tensile ($\varepsilon < 0$, $\varepsilon = -0.32\%$ for CdTe buffer) to compressive ($\varepsilon > 0$, up to $+1.40\%$). Following this idea, we have performed calculations of the critical width $d_c$ and the Fermi velocity $v_F$ for the QWs with 2D massless Dirac fermions ($B_c = 0$ T) at different strains and at temperatures up to 100 K.

The calculations were made for the QWs grown along the (001) direction. It is worth noting, however, that the results for the (013) QWs are qualitatively the same. The calculated low-temperature (~1.5 K) energy dispersions, for two HgTe QWs hosting massless Dirac fermions for strain $\varepsilon = -0.32\%$ (CdTe buffer) and $\varepsilon = 1.3\%$, are shown in Fig. 6a and b. One should notice that the critical width $d_c$ is different for these two structures: $d_c = 6.4$ nm and $d_c = 4.6$ nm, respectively. In Fig. 6c we show the critical QW width $d_c$ as a function of strain and temperature. One can see that with increase of temperature from 1 to 100 K, the critical width $d_c$ increases by about 30%. It can be also seen (Fig. 6e) that the compressive strain indeed leads to an increase of the Fermi velocity ($v_F$) of the 2D massless Dirac fermions. Note that energy difference between the position of the side maxima into the valence band and charge neutrality point also raise with strain enhancement (see Fig. S2 in supplementary materials). Results presented in Fig. 6 indicate the ways of HgTe QWs engineering, in view of their applications for resistance standards.

To illustrate the advantages of HgTe QWs as the QHE resistance standards, in Fig. 6, we compare the energy spacing between the LLs ($\Delta$) at the quantum limit conditions ($\nu = 1$) for G/SiC, GaAs/(Al, Ga)As QWs and the investigated HgTe/(Cd,Hg)Te QWs. It is conventionally assumed that thermal excitations cease to be relevant for metrological applications for $\Delta \geq 100 k_B T$, corresponding to $\Delta \geq 13$ meV at $T=1.5$ K. The second condition is $\mu B > 1$, where $\mu$ is the carrier mobility that determines the degree of the LL energy broadening. Both conditions, $\mu B > 1$ and $\Delta \geq 100 k_B T$, merge together, defining the metrological regions marked in Fig. 6d.

The second, the magnetic field condition, is a limiting factor for G/SiC for which the $\mu = 1 m^2 V^{-1} s^{-1}$ and $\mu B > 1$ conditions are fulfilled only for a magnetic field $B > 1$ T. In HgTe QW samples (mobility ~ $10^7 m^2 V^{-1} s^{-1}$), this condition is fulfilled already at $B \geq 0.1$ T. One can see that the metrological range for HgTe QWs samples may be obtained in relatively lower magnetic fields.

The optimum $T \approx 1.5$ K metrological conditions for HgTe QWs are predicted with $d = 6.4$ nm ($\varepsilon = -0.32\%$) and $d = 4.6$ nm ($\varepsilon = 1.3\%$) for $B = 0.3$ T and $B \approx 0.5$ T, respectively. These QWs are hosting Dirac fermions with normal band ordering, ensuring maximum Landau level splitting and absence of topological edge conducting channels. Figure 6 clearly shows that HgTe based QWs
may be interesting for QHE standards developments because they may have graphene-like band structure (large Landau level splitting) and simultaneously they may host very high mobility carriers. These considerations demonstrate that there is a considerable room for optimizing the performance and for demonstrating the practical relevance of resistance standards of HgTe quantum wells.

DISCUSSION

Although we show possibility to reach, using HgTe QWs, favorable cryomagnetic conditions for QHE metrology—the real metrological applications require some important developments. They are very well illustrated by the work on graphene based QHE metrology sensors. The most important developments necessary in the case of HgTe QW are discussed below.

First of all—as stated in the main part of the paper—one has to grow narrower QWs with—direct (non-inverted band structure) and if possible with compressive strain that leads to enhancement of the Fermi velocity (enhanced Landau level splitting). But, to reach a metrological precision one needs not only non-inverted band structure QWs (avoiding edge channel parasitic conduction) but also provide samples operating with the highest possible current. The current can be increased by processing devices with bigger geometrical dimensions and with smaller contact resistance. This current is usually limited not only by the sample

Fig. 6  a, b Calculated energy dispersions for two HgTe QWs hosting massless Dirac fermions for \(d = 6.4 \text{ nm}, \epsilon = -0.32\% \) (CdTe buffer) and \(d = 4.6 \text{ nm}, \epsilon = 1.3\%\), respectively. c Critical QW width \(d_c\) as a function of strain and temperature. d Energy gap \(\Delta\) between two lowest LLs of the valence band at \(\nu = -1\) as a function of the magnetic field for these two QWs (solid red and black curves, respectively) as well as for samples S1 (orange line) and S3 (cian line); data for graphene (blue line) and GaAs/AlGaAs (green line) are also shown. The gray horizontal line is the lower boundary of the metrological range \(\Delta \geq 100k_B T\) at \(T = 1.5\ K\). Vertical gray dashed lines indicate metrologically useful range where condition \(\mu B \geq 1\) is fulfilled. Points at which two conditions starts execute marked by stars. e Band velocity \(v_F\) of massless Dirac fermions vs. strain
geometry and contacts quality but also by carrier heating phenomena leading to QHE breakdown. Different carrier heating phenomena may be specific for each material depending on strength of electron–phonon interaction or phenomena of the charge transfer between the carriers and the reservoir. The research on the maximization of QHE breakdown current is surely one of the most important tasks—for future research on metrological applications of HgTe QWs.

In our experiments the highest precision of QHE resistance (in the 10⁻⁴) was obtained. This precision is still far from being acceptable for metrological applications but we believe that it can be reached once mentioned above technological developments concerning correct band structure, sample geometry and contact resistance are successfully overcome.

To summarize, we have investigated the HgTe/(Cd,Hg)TeX QWs in view of their application for new competitive QHE standards. We have shown that the coexistence of helical quantum spin Hall states and conventional chiral quantum Hall states in the topologically non-trivial region (δ > δc, B < Bc) may restrict the accuracy of the Hall resistance quantization. At the same time, our results demonstrate that for the non-inverted QWs close to the critical width δc at which Dirac fermions control the charge transport and charge transfer mechanisms ensure wide plateaus (“charge reservoir” model), the QHE metrological conditions can be reached for holes (p-type samples) in very favorable measurement techniques. High-precision resistance measurements were performed using the 8 T superconducting magnet system and standard lock-in thermometry. Indium soldering. The magnetotransport experiments have been carried out using FEI Titan 80–300 electron microscope equipped with the image corrector operating at 300 kV.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors on request.

ACKNOWLEDGEMENTS

The research in Poland was partially supported by the Foundation for Polish Science through the IRA Program financed by EU within SG OP Program and No. TEAM/2016-3/25, by the National Science Centre, Poland, decisions No. DEC-2011/02/A/ST3/00125, 2013/10/M/ST3/00705, UMO-2015/17/N/ST3/02314, 2016/22/ST7/00526, and UMO-2017/25/N/ST3/00408. The authors also acknowledge Russian Foundation for Basic Research (Grants 15-52-16008 and 16-02-00072), ARPE TeraSens project and Terahertz Platform both provided by Occitanie Region. The theoretical calculations for the compressively strained QWs were performed in the framework of project 16-12-10317, supported by the Russian Science Foundation. S.K. and A.K. acknowledge the Russian Ministry of Education and Science (MK-1136.2017.2 and SP-5051.2018.5). The authors gratefully thank Z.D. Kvon from the Institute of Semiconductor Physics (Siberian Branch, Russian Academy of Sciences) for stimulating and fruitful discussions as well as for providing the processed gate Hall bar samples.

AUTHOR CONTRIBUTIONS

I.Y., G.G., B.J., C.C., W.D., A.M.K., D.B.B. and G.G. have contributed to the experiments. The sample growth was performed by S.A.D. and N.N.M. The sample processing and TEM investigations were performed by M.M., J.W. and S.K. Theoretical calculations were made by S.S.K., K.E.S., V.I.G. and T.D. All co-authors have participated in the discussion of the data. The paper and supplementary information were written by W.K., I.Y., S.S.K., G.G., T.D., F.T. and B.J.

ADDITIONAL INFORMATION

Supplementary Information accompanies the paper on the npj Quantum Materials website (https://doi.org/10.1038/s41535-019-0154-3). Competing interests: The authors declare no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

1. Dornhaus, R., Nimtz, G. & Schlicht, B. Narrow-Gap Semiconductors. (Springer, Berlin, Heidelberg, 1983).
2. Gałązka, R. & Sosnowski, L. Conduction Band Structure of Cd1-xHgxTe. Phys. Stat. Sol. (a) 110, 113–120 (1967).
3. Orlita, M. et al. Observation of three-dimensional massless Kane fermions in a zinc-blende crystal. Nat. Phys. 10, 233–238 (2014).
4. Tepe, F. et al. Temperature-driven massless Kane fermions in HgCdTe crystals. Nat. Commun. 7, 12576 (2016).
5. Dubovski, J., Dietl, T., Szymańska, W. & Galazka, E. Electron scattering in Cd1-xHgxTe. J. Phys. Chem. Solids 42, 351–362 (1981).
6. Ruffenhaush, S. et al. HgCdTe-based heterostructures for Terahertz photodetectors: a review. Rep. Prog. Phys. 79, 046501 (2016).
7. Morozov, S. et al. Stimulated emission from HgCdTe quantum well heterostructures at wavelengths up to 19.5 µm. Appl. Phys. Lett. 111, 192101 (2017).
8. König, M. et al. Quantum spin Hall insulator state in HgTe quantum wells. Science 318, 766–770 (2007).
9. König, M. et al. The quantum spin Hall effect: theory and experiment. J. Phys. Soc. Jpn. 77, 031007 (2008).
10. Brüne, C. et al. Quantum Hall effect from the topological surface states of strained bulk HgTe. Phys. Rev. Lett. 106, 126803 (2011).
11. Qi, X.-L. & Zhang, S.-C. Topological insulators and superconductors. Rev. Mod. Phys. 83, 1057–1110 (2011).
12. Ortmann, F., Roche, S. & Valenzuela, S. O. Topological Insulators: Fundamentals and Perspectives. (John Wiley & Sons, Hoboken, 2015).
13. Büttner, B. et al. Single valley Dirac fermions in zero-gap HgTe quantum wells. Nat. Phys. 7, 418–422 (2011).
15. Krishtopenko, S. S., Knop, W. & Tepe, F. Phase transitions in two tunnel-coupled HgTe quantum wells: bilayer graphene analogy and beyond. Sci. Rep. 6, 30755 (2016).
16. Piotrowski, J. & Rogalski, A. High-Operating Temperature Infrared Photodetectors. (SPIE Press, Bellingham, WA, 2007).
17. Dvoretsky, S. et al. Growth of HgTe quantum wells for IR to THz detectors. J. Electron. Mater. 39, 918–923 (2010).
18. Klitzing, K. v., Dorda, G. & Pepper, M. New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance. Phys. Rev. Lett. 45, 494–497 (1980).
19. Tong, D. Lectures on the Quantum Hall Effect. https://arxiv.org/abs/1606.06687 (2016).
20. Poirier, W. & Schopfer, F. Resistance metrology based on the quantum Hall effect. Eur. Phys. J.: Spec. Top. 172, 207–245 (2009).
21. Jeckelmann, B. & Jeanneret, B. The quantum Hall effect as an electrical resistance standard. Rep. Prog. Phys. 64, 1603–1655 (2001).
22. Janssen, T. J. B. M., Tzalenchuk, A., Lara-Avila, S., Kubatkin, S. & Fal’ko, V. I. Quantum resistance metrology using graphene. Rep. Prog. Phys. 76, 104501 (2013).
23. Taylor, B. N. & Witt, T. J. New international electrical reference standards based on the Josephson and quantum Hall effects. Metrology 26, 47–62 (1989).
24. Chang, C.-Z. et al. Experimental observation of the quantum anomalous Hall effect in a magnetic topological insulator. Science 340, 167–170 (2013).
25. Fox, E. J. et al. Part-per-million quantization and current-induced breakdown of the quantum anomalous Hall effect. Phys. Rev. B 98, 075145 (2018).
26. Götz, M. et al. Precision measurement of the quantized anomalous Hall resistance at zero magnetic field. Appl. Phys. Lett. 112, 072102 (2018).
27. Parmentier, F. D. et al. Quantum Hall effect in epitaxial graphene with permanent magnets. Sci. Rep. 6, 38393 (2016).
28. Ribeiro-Palau, R. et al. Quantum Hall resistance standard in graphene devices under relaxed experimental conditions. Nat. Nanotechnol. 10, 965–971 (2015).
29. Janssen, T. J. B. M. et al. Operation of graphene quantum Hall resistance standard in a cryogen-free table-top system. 2D Mater. 2, 035015 (2015).
30. Lafont, F. et al. Quantum Hall resistance standards from graphene grown by chemical vapour deposition on silicon carbide. Nat. Commun. 6, 6806 (2015).
31. Novoselov, K. S. et al. Room-temperature quantum Hall effect in graphene. Science 315, 1379 (2007).
32. Lara-Avila, S. et al. Non-volatile photochemical gating of an epitaxial graphene/polymer heterostructure. Adv. Mater. 23, 878–882 (2011).
33. Yang, M. et al. Puddle-induced resistance oscillations in the breakdown of the graphene quantum Hall effect. Phys. Rev. Lett. 117, 237702 (2016).
34. Kozlov, D. A., Kvon, Z. D., Mikhailov, N. N. & Dvoretsky, S. A. Quantum Hall effect in a system of gapless Dirac fermions in HgTe quantum wells. JETP Lett. 100, 724–730 (2015).
35. Kozlov, D. et al. Quantum Hall effect in HgTe quantum wells at nitrogen temperatures. Appl. Phys. Lett. 105, 132102 (2014).
36. Khouri, T. et al. High-temperature quantum Hall effect in finite gapped HgTe quantum wells. Phys. Rev. B 93, 125308 (2016).
37. Vaimann, T., Kallaste, A., Kilk, A. & Belashchen, A. Magnetic properties of reduced Dy NdFeB permanent magnets and their usage in electrical machines. IEEE Xplore https://doi.org/10.1109/AFRICTON.2013.6757787 (2014).
38. Richardson, R. C. & Smith, E. N. Experimental Techniques in Condensed Matter Physics at Low Temperatures. (Advanced Book Classics, USA, 2018).
39. Giesbers, A. J. M. et al. Quantum resistance metrology in graphene. Appl. Phys. Lett. 93, 222109–222112 (2008).
40. Guignard, J., Leprat, D., Glattli, D. C., Schopfer, F. & Poirier, W. Quantum Hall effect in exfoliated graphene affected by charged impurities: metrological measurements. Phys. Rev. B 85, 165420 (2012).
41. Rigosi, A. F. et al. Graphene devices for tabletop and high current quantized Hall resistance standards. IEEE Proceedings https://doi.org/10.1109/ICTInternational2018/882958 (2018).
42. Majewicz, M. et al. Low temperature processing of nanostructures based on II–VI semiconductors quantum wells. Acta Phys. Pol. A 126, 1174–1176 (2014).
43. Krishtopenko, S. S. et al. Pressure- and temperature-driven phase transitions in HgTe quantum wells. Phys. Rev. B 94, 245402 (2016).
44. Kadykov, A. M. et al. Temperature-induced topological phase transition in HgTe quantum wells. Phys. Rev. Lett. 120, 086401 (2018).
45. Marcinkiewicz, M. et al. Temperature-driven single-valley Dirac fermions in HgTe quantum wells. Phys. Rev. B 96, 035405 (2017).
46. Zholudev, M. et al. Magneto-spectroscopy of two-dimensional HgTe-based topological insulators around the critical thickness. Phys. Rev. B 86, 205420 (2012).
47. Chen, J.-C., Wang, J. & Sun, Q.-F. Effect of magnetic field on electron transport in HgTe/CdTe quantum wells: numerical analysis. Phys. Rev. B 85, 125402 (2012).
48. Ma, E. Y. et al. Unexpected edge conduction in mercury telluride quantum wells under broken time-reversal symmetry. Nat. Commun. 6, 7252 (2015).
49. Grabbeck, G. et al. Nonlocal resistance and its fluctuations in microstructures of band-inverted HgTe/HgCdTe quantum wells. Phys. Rev. B 88, 165309 (2013).
50. Zawadzki, W., Raymond, A. & Kubisa, M. Reservoir model for two-dimensional electron gases in quantizing magnetic fields: a review. Phys. Status Solidi B 251, 247–262 (2014).
51. Kopylov, S., Tzalenchuk, A., Kubatkin, S. & Fal’ko, V. I. Charge transfer between epitaxial graphene and silicon carbide. Appl. Phys. Lett. 97, 112109 (2010).
52. Janssen, T. J. B. M. et al. Anomalously strong pinning of the filling factor ν=2 in epitaxial graphene. Phys. Rev. B 83, 234302 (2011).
53. Leubner, P., Lunczer, L., Brüne, C., Buhmann, H. & Molenkamp, L. W. Strain engineering of the band gap of HgTe quantum wells using superlattice virtual substrates. Phys. Rev. Lett. 117, 086403 (2016).
54. Krishtopenko, S. S. & Tepe, F. Realistic picture of helical edge states in HgTe quantum wells. Phys. Rev. B 97, 165408 (2018).
55. Janssen, T. J. B. M. et al. Precision comparison of the quantum Hall effect in graphene and gallium arsenide. Metrology 49, 294–306 (2012).