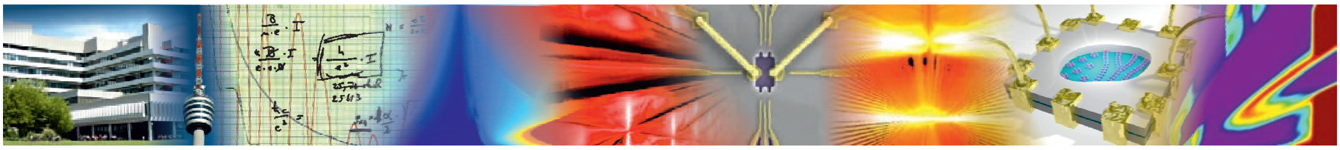
# Quantum Hall Effects and Related Topics



International Symposium

Stuttgart, June 27th – 29th, 2018

Max Planck Institute for Solid State Research

**General Information, Program, and Abstracts**

# CONTENTS

# PREFACE

## Purpose

The quantum Hall effect was discovered in 1980 by Klaus von Klitzing. Since 1990, the quantum Hall effect has been used as electrical resistance standard in metrology because of its unprecedented precision. In November 2018 the General Conference on Weights and Measures – the supreme authority of the International Bureau of Weights and Measures – will decide about a change in the definition of the physical base units of the International System (SI). The revised definitions will be based on seven constants of nature with the kilogram prototype replaced by a fixed value for the Planck constant. The integer quantum Hall effect played with its precision a key role in this development.

Apart from this further ramification of the quantum Hall effect in everybody's life, quantum Hall samples turned out to be an excellent playground to study exciting effects arising by the interaction in a many-electron system. New phenomena have been discovered. Early on, it triggered the discovery of the fractional quantum Hall effect, which was continued with that of composite fermions, striped phases, and exciton condensation in quantum Hall bilayers, to name just a few. Novel materials as graphene or the topological insulators became particularly exciting after they were found to show the quantum Hall effect.

The Symposium will provide the opportunity to meet many of the leading researchers in the field of quantum Hall physics for discussing the status and the exciting developments both in basic research and in metrology.

## Topics

Distinguished invited speakers will give 30 min presentations on selected topics. Poster contributions have been invited on the following topics:

- Quantum Hall systems
- QHE and the new SI units
- Growth of state-of-the art 2DES
- Exotic quantum Hall states
- Exciton condensation in 2D bilayers
- Topological insulators
- Graphene and other 2D materials
- Oxide heterostructures
- Quasiparticles in low-dimensional electron systems

## Honorable Chairman of the Symposium

Klaus **von Klitzing** (Max Planck Institute for Solid State Research, Germany)

## Invited Speakers

Tsuneya **Ando** (Tokyo Institute of Technology, Japan)
Ray **Ashoori** (MIT, Boston, USA)
Gabor **Csáthy** (Purdue University, USA)
Rui-Rui **Du** (Rice University, USA / Beijing University, China)
Jim **Eisenstein** (California Institute of Technology (Caltech), USA)
Vladimir **Fal´ko** (Manchester University, United Kingdom)
David **Goldhaber-Gordon** (Stanford University, USA)
Bert **Halperin** (Harvard University, USA)
Moty **Heiblum** (Weizmann Institute of Science, Israel)
Yoshiro **Hirayama** (Tohoku University, Japan)
Jainendra **Jain** (Penn State University, USA)
Jan-Theodoor **Janssen** (National Physical Laboratory, United Kingdom)
Nobu-Hisa **Kaneko** (National Metrology Institute of Japan)
Masashi **Kawasaki** (University of Tokyo, Japan)
Philip **Kim** (Harvard University, USA)
Allan **MacDonald** (University of Texas at Austin, USA)
Charlie **Marcus** (The Niels Bohr Institute, Denmark)
Martin J. T. **Milton** (Bureau International des Poids et Mesures, Paris, France)
Koji **Muraki** (NTT Basic Research Laboratories, Japan)
Mansour **Shayegan** (Princeton University, USA)
Joachim **Ullrich** (Physikalisch Technische Bundesanstalt, Germany)
Dieter **Weiss** (University of Regensburg, Germany)
Barry **Wood** (National Research Council, Ottawa, Canada)
Qi-Kun **Xue** (Tsinghua University, China)
Amir **Yacoby** (Harvard University, USA)
Eli **Zeldov** (Weizmann Institute of Science, Israel)

## Invited Chairpersons

Gerhard **Abstreiter** (Walter-Schottky-Institute, Munich, Germany)
Günther **Bauer** (University of Linz, Austria)
Klaus **Ensslin** (ETH Zurich, Switzerland)
Chihiro **Hamaguchi** (Osaka University, Japan)
Rolf **Haug** (University of Hannover, Germany)
Friedemar **Kuchar** (University of Leoben, Austria)
Daniela **Pfannkuche** (University of Hamburg, Germany)
Gloria **Platero** (Material Science Institute of Madrid, Spain)

## Participants

In addition, more than 100 participants have registered for this Symposium, coming from Asia, America and Europe, complemented by scientists from the Institute joining the talks.

## Posters

Submitted by participants, about 40 poster contributions have been accepted. The posters will be accessible throughout the whole Symposium.

## Organizing Commitee

Jurgen H. **Smet**
Solid State Nanophysics, Max Planck Institute for Solid State Research, Germany
http://www.fkf.mpg.de/SNP

Jürgen **Weis**
Nanostructuring Lab, Max Planck Institute for Solid State Research, Germany
http://www.fkf.mpg.de/NSL

## Symposium Site

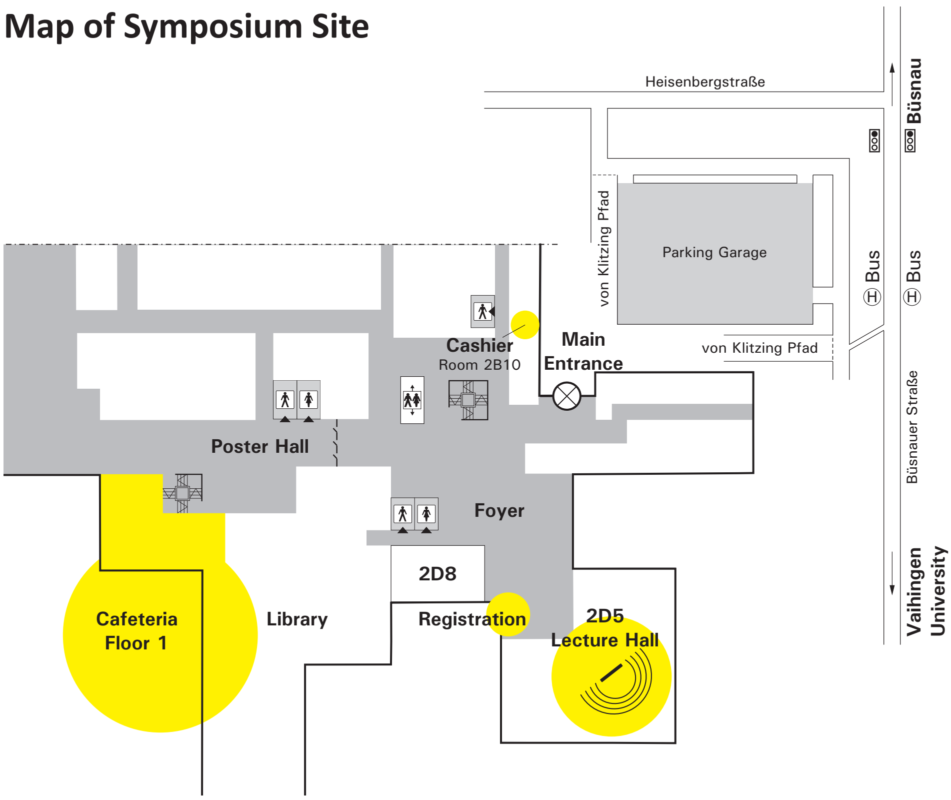
Max-Planck-Institut für Festkörperforschung
(Max Planck Institute for Solid State Research)
Heisenbergstraße 1
70569 Stuttgart, Germany

http://www.fkf.mpg.de

## Symposium Website

http://www.fkf.mpg.de/QHE2018

## Map of Symposium Site




## WLAN Connection

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| WLAN (SSID): | **conference** |
| Password (PSK): | **QHE062018** |

## Registration Desk

Secretary: Ruth **Jenz**
Phone: +49 711 689-1287

## Photo, Video and Audio Recording of Talks and Posters

Please note, your recording of talks and posters (photo, video and audio) requires the permission by the respective presenter in advance!

The Symposium team will take photos during the sessions and breaks. A selection of them will become available to the invited and registered participants of the Symposium. If you do not want to be present on these photos, please contact the Symposium organizers or the respective photographer.

## Lunches

The lunches on Wednesday, Thursday and Friday in the Cafeteria of the MPI are included in the conference fee. For lunch there will be three meals and a salad bar offered.

## Public Session (Wednesday, June 27th, 14:00 - 18:00)

The first two sessions of the Symposium are dedicated to the

**Redefinition of the Physical Base Units (SI Units) ,**

and are announced as public sessions at the neighboring Universities of Stuttgart, Tübingen and Ulm.

## Poster Session (Wednesday evening, June 27th)

The posters will be accessible throughout the whole Symposium, however on Wednesday evening a special poster session is scheduled from 18:00 to 20:00. Fingerfood will be offered close-by. Afterwards, there will be a get-together till 22:00 in the Cafeteria and Garden of the Institute with beer, wine, soft drinks, bread, and cheese.

## Symposium Dinner (Thursday evening, June 28th)

The Symposium Dinner will take place on Thursday evening, in Stuttgart downtown at the Restaurant Cube, starting at 18:45 with the reception:

http://www.cube-restaurant.de

Three busses going downtown will leave from the Symposium site (MPI). One of these busses will drive at 18:00 via the Relexa Hotel Schatten, waiting there till 18:30 before going downtown. The two other busses will leave at 18:15 from the MPI and will go directly downtown. After the Symposium Dinner at 23:00, the busses will return to the MPI and the Relexa Hotel Schatten.

## Closing Event (Friday evening, June 29th)

On Friday evening, three busses will leave at 17:30 to the Villa Benz in Kirchheim unter Teck

http://www.villabenz.de

where we will have a relaxed get-together with grill buffet. One of these busses will drive via the Relexa Hotel Schatten, waiting there till 18:15 before going to Villa Benz. The two other busses will leave from the MPI and will go directly to the Villa Benz. Between 22:30 and 23:00, the busses will return to the S-Bahn Station Universität, the MPI and the Relexa Hotel Schatten.

# PROGRAM

## Wednesday, June 27th

| | |
|---|---|
| 12:00 | Opening of On-Site Registration<br>*Coffee, tea and soft drinks in the Entrance Hall* |
| Welcome | Lecture Hall |
| 14:00 | **Walter Metzner**<br>Managing Director of the MPI for Solid State Research<br>**Klaus von Klitzing**<br>Honorable Chairman of the Symposium |
| **Session 1** | Chair: Klaus von Klitzing |
| 14:35 | **Martin J. T. Milton**<br>The re-definition of the base units of the SI: using the rules of nature to create the rules of measurement |
| 15:10 | **Joachim Ullrich**<br>The International System of Units: From the French Revolution to the Quantum SI |
| 15:45 | *Coffee Break in Entrance Hall* |
| **Session 2** | Chair: **Klaus von Klitzing** |
| 16:15 | **Barry Wood**<br>The Quantum Hall Effect -The Key to SI Redefinition |
| 16:50 | **Jan-Theodoor Janssen**<br>A new era for the SI and the quantum Hall effect |
| 17:25 | **Nobu-Hisa Kaneko**<br>Development of 1 MΩ quantum Hall array and error modelling of wire and contact resistances |
| 18:00 | Poster Session in the Poster Hall with finger food |
| 20:00 | *Get-Together with beer and wine in the Cafeteria / Garden* |
| 22:00 | *Closing of bar* |

## Thursday, June 28th

**Session 3** Chair: **Gerhard Abstreiter**

9:00 **Jim Eisenstein**
Interlayer interactions and tunneling in bilayer composite fermion metals

9:35 **Rui-Rui Du**
Topological Excitonic Condensation and Beyond in Double Quantum Wells

10:10 **Philip Kim**
Interlayer Excitons and Magneto-Exciton Condensation in van der Waals Heterostructures

10:45 *Coffee Break in Entrance Hall*

**Session 4** Chair: **Daniela Pfannkuche**

11:15 **Vladimir Fal´ko**
Moire superlattice effects and Brown-Zak minibands in graphene

11:50 **Allan MacDonald**
Double Bilayer Graphene Excitonic Superfluids

12:25 *Conference Photo*

12:30 *Lunch in the Cafeteria*

**Session 5** Chair: **Klaus Ensslin**

14:00 **Moty Heiblum**
Quantization of heat flow in the FQHE regime

14:35 **David Goldhaber-Gordon**
Chiral 1D transport in magnetic topological insulators: precise quantization and manipulation

15:10 **Koji Muraki**
Probing the Bulk and Edge States in InAs-based Heterostructures

15:45 *Coffee Break in Entrance Hall*

**Session 6** Chair: **Rolf Haug**

16:15 **Ray Ashoori**
Momentum, Energy, and Spin Resolved Tunneling of Quantum Hall States

16:50 **Amir Yacoby**
Exploring Magnonic Excitation in Quantum Hall Ferromagnets

17:25 **Dieter Weiss**
A brief history of my time with Klaus von Klitzing

18:00 *Busses leaving to Restaurant Cube at downtown Stuttgart*

18:45 *Reception at the Restaurant*

19:15 *Conference Dinner*

23:00 *Busses leaving to Relexa Hotel and MPI*

## Friday, June 29th

**Session 7** Chair: **Günther Bauer**

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| 9:00 | **Qi-Kun Xue**<br>New progress in quantum anomalous Hall effect |
| 9:35 | **Tsuneya Ando**<br>Topological Phenomena and Anomaly in Graphene |
| 10:10 | **Jainendra Jain**<br>Progress towards quantitative understanding of the fractional quantum Hall effect |
| 10:45 | *Coffee Break in Entrance Hall* |

**Session 8** Chair: **Chihiro Hamaguchi**

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|---|---|
| 11:15 | **Masashi Kawasaki**<br>Quantum mechanical shift current |
| 11:50 | **Yoshiro Hirayama**<br>Resistively-Detected Nuclear-Magnetic-Resonance in Microscopic Scale |
| 12:25 | *Lunch in the Cafeteria* |

**Session 9** Chair: **Friedel Kuchar**

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|---|---|
| 14:00 | **Mansour Shayegan**<br>Nematic Phases in 2D Electron Systems:<br>Role of Mass Anisotropy and Magnetization |
| 14:35 | **Gabor A. Csáthy**<br>Competing Fractional Quantum Hall and Nematic Phases in the Half-filled Second Landau Level |
| 15:10 | **Bertrand I. Halperin**<br>Open questions about a Landau level near half-filling |
| 15:45 | *Coffee Break in Entrance Hall* |

**Session 10** Chair: **Gloria Platero**

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|---|---|
| 16:15 | **Eli Zeldov**<br>Nanoscale thermal imaging:<br>Glimpse into dissipation in quantum systems |
| 16:50 | **Charlie Marcus**<br>Using Topology to Build a Better Qubit |

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|---|---|
| 17:30 | *Busses leaving to Villa Benz, Kirchheim unter Teck* |
| 18:15 | *Reception at Villa Benz* |
| 19:00 | *Buffet* |
| 22:30 & 23:00 | *Busses leaving to S-Bahn University, MPI and Relexa Hotel* |

# Abstracts of Talks

# TALKS

# The re-definition of the base units of the SI: using the rules of nature to create the rules of measurement

Martin J. T. Milton

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In November 2018, the General Conference on Weights and Measures is expected to agree one of the most significant changes to the base units of the International System (the SI) which will base them on a set of definitions each linked to the laws of physics. This historic change towards using the laws of nature in the definitions will eliminate the final link between the SI and definitions based on physical artefacts. Following the revisions, the kilogram will be linked to the exact value of the Planck constant rather than the International Prototype of the Kilogram, as sanctioned by the 1st CGPM in 1889.

For over 200 years, a collective ambition for the "metric system" has been to provide universality of access to the agreed basis for worldwide measurements. The changes to the definitions of the kilogram, the ampere, the kelvin and the mole that are expected to be agreed in November will be a further step towards this goal. They are based on the results of research into new measurement methods such as the Kibble balance [1] and the application of X-ray crystal diffraction to determine the number of atoms in isotopically-pure silicon [2]. They make use of the Josephson effects [3] and the quantum Hall effect [4] to link them to quantum phenomena. Substantial experimental efforts have been made by measurement institutes around the world to agree on values for the Planck constant and the Boltzmann constant with relative uncertainties of $1{\cdot}10^{-8}$ and $3.7{\cdot}10^{-7}$ respectively. These will ensure that the new definitions will be compatible with the current ones at the time the change is implemented.

Whilst providing the necessary level of continuity for existing users, the changes have the advantage of being able to embrace future improvements in measurement methods to meet the needs of future users because they are based on the laws of physics. The new definitions will use "the rules of nature to create the rules of measurement" thus linking measurements at the atomic and quantum scales to those at the macroscopic level.

## References

[1] B. P. Kibble, A measurement of the gyromagnetic ratio of the proton by the strong field method, in: Atomic Masses and Fundamental Constants, edited by J. H. Sanders and A. H. Wapstra, New York: Plenum, pp. 545-551 (1976).
[2] B. Andreas *et al.* Physical Review Letters **106**, 030801 (2011).
[3] B. N. Taylor *et al.* Metrologia **3**, 89 (1967).
[4] K. von Klitzing *et al.* Physical Review Letters **45**, 494 (1980).
[5] P. J. Moore *et al.* Metrologia **55**, 125 (2018).

# The International System of Units: From the French Revolution to the Quantum SI

Joachim Ullrich

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In November 2018, it is anticipated that at the 26th meeting of the General Conference on Weights and Measures, CGPM, established by the Metre Convention in 1875, will decide to revise the International System of Units (SI). As outlined by Max Planck in his famous paper of 1900 postulating the "Planck constant", this revised SI-System shall be based on fixing the numerical values of "defining constants": the velocity of light, the elementary charge, the Boltzmann, Avogadro and the Planck constants, the Cs hyperfine clock transition and the luminous efficacy. The elimination of artefacts in this revised SI, which is sometimes dubbed as the "quantum SI", is based on our present theoretical understanding of the microscopic world.  The revision is meant to ensure that it is valid and realizable “for all of time, for all people”, the vision formulated during the French revolution and as extended by Max Planck, "for all times and civilizations, throughout the Universe".

In the talk the evolution of the SI "from artefacts to quanta" will be briefly outlined with emphasis on the decisive role of the von Klitzing constant in establishing the revised SI. This will be followed by highlighting some of the most important developments in future quantum electrical standards; some point towards a new generation of shot-noise free electronics, which would certainly support what is sometimes dubbed the "second quantum revolution".

Finally, if time allows, major current developments in the realisation and dissemination of the second will be reported. For example, new next-generation optical clocks using transitions in highly-charged ions, that are read out via quantum-logic schemes, will support the investigation of the question if the fundamental constants are indeed constant in time. New optical clocks have the chance to trace potential changes in the fine structure constant $\alpha$ at the level of $\Delta\alpha/\alpha \approx 10^{-20}$ per year.

# The quantum Hall effect – The Key to SI Redefinition

Barry Wood

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Klaus von Klitzing discovered the quantum Hall effect in 1980 and one of its immediate impacts was to revolutionize electrical metrology. Countries around the world seized on this technique to stabilize resistance standards and to couple their measurement system to an intrinsic quantum standard.

Now, some 38 years later, the world is on the threshold of fully integrating this and other quantum standards into our measurement system, the SI. In November of this year the 58 countries that make up the member states of the Metre Convention are expected to approve a revision of the SI. In essence the change is based on assigning fixed values to seven reference constants and deriving measurement units from those constants using the laws of physics. Those seven constants include five fundamental constants of nature; the speed of light, the elementary charge, the Planck constant, the Boltzmann constant and the Avogadro constant. This type of change has been advocated for more than a century but its final implementation has been delayed, primarily due to the limited accuracy of the value of the Planck constant, $h$.

I will outline the revised SI and the determination of the value of the Planck constant using a Kibble balance. I will explain how the quantum Hall effect is a critical part of these measurements and present the experimental data that contributed to setting the final value of $h$. Finally, I will explain my claim: that without the quantum Hall effect, we would not be revising the SI in 2018.

# A new era for the SI and the quantum Hall effect

Jan-Theodoor Janssen

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In the autumn of this year the international system of units is set to undergo its biggest change since its inception. Four of the seven SI base units will change their definition and be forever linked to fundamental constants of nature. The quantum Hall effect has played a key role in this redefinition process and will also be affected by it: The Ohm will come back into the SI system and von Klitzing will lose his constant.

In recent years, aided by the discovery of graphene, the universality of the quantum Hall effect could be tested at an unprecedented level of accuracy. In addition, the unique properties of graphene have allowed us to develop a small table-top quantum Hall system which will allow many more laboratories to realise primary traceability, bringing the QHE to the masses.

# Development of 1 MΩ quantum Hall array and error modelling of wire and contact resistances

Nobu-Hisa Kaneko[1], Dong-Hun Chae[2], Wan-Seop Kim[2], Takehiko Oe[1], Martina Marzano[3,4], Massimo Ortolano[3,4], and Luca Callegaro[4]

[1]National Metrology Institute of Japan, National Institute of Advanced Industrial Science & Technology, Tsukuba, Ibaraki 305-8563, Japan
[2]Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea
[3]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[4]Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce, 91, 10135 Torino, Italy

Email: nobuhisa.kaneko@aist.go.jp

We report precision measurements of a 1 MΩ quantum Hall array resistance standard (QHARS) made of GaAs/AlGaAs heterostructure, that was fabricated at the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) [1]. Figure 1 shows a schematic diagram and a picture of the 1 MΩ QHARS circuit/device and magnetic field dependence at a temperature of 0.3 K. At the Korea Research Institute of Standards and Science (KRISS), the QHARS at filling factor 2 has been directly compared with the quantum Hall resistance standard with a cryogenic current comparator (CCC) resistance bridge [2] with a relative measurement uncertainty of $17{\cdot}10^{-9}$ at the 95% confidence level. Figure 2 (a) shows a schematic diagram of the KRISS CCC resistance bridge for a direct comparison of the QHARS and a conventional single-Hall-bar QHR standard. Relative deviation of the QHARS from the designed value at filling factor 2 for repeated measurements at a temperature of 0.3 K is shown in Figure 2(b). The duration of each measurement was approximately 30 minutes. The robustness of quantization in the array has been also systematically investigated with respect to the temperature, magnetic field, and excitation current. We have observed through repeated thermal cycles that the quantized Hall array resistance is almost unchanged within the relative measurement uncertainty, reflecting the invariant nature of high resistance close to 1 MΩ.

This demonstrates a stable quantum mechanical resistance of 1 MΩ as well as the potential for a genuine current-to-voltage converter for precision measurements of small current. The observed relative deviation of the quantized Hall array resistance from a designed value, verified by a double consistency check through a 10 kΩ resistance standard and the Hall array resistance plateau at filling factor 4, respectively, is comparable to the relative measurement uncertainty. Not only the experimental results, we will also discuss a general and systematic procedure for the error modelling of the QHARS taking contact and wire resistance into account, which is based on modern circuit analysis techniques and Monte Carlo evaluation of the uncertainty.

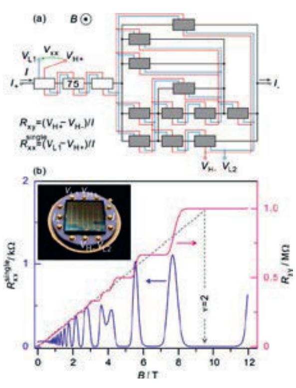

**Fig. 1:** (a) Schematic diagram of the 1 MΩ QHR array circuit. (b) Magnetic field dependence at a temperature of 0.3 K. Inset shows a photograph of the measured 1 MΩ QHR array.

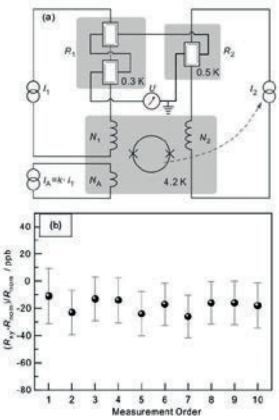

**Fig. 2:** (a) Schematic diagram of the cryogenic current comparator resistance bridge for the direct comparison. (b) Relative deviation of the QHAR from the designed value at filling factor 2 for repeated measurements at a temperature of 0.3 K.

## References

[1] T. Oe *et al*. IEEE Transactions *on* Instrumentation and Measurement **66**, 1475 (2017).
[2] W.-S. Kim *et al*. Journal of the Korean Physical Society **58**, 13392 (2011).
[3] M. Marzano *et al*. Metrologia **55**, 167 (2018).

# Interlayer interactions and tunneling in bilayer composite fermion metals

Jim P. Eisenstein[1], L. N. Pfeiffer[2], and K. W. West[2]

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It is well known that when two 2D electron gas layers, each at filling factor $\nu = 1/2$, are brought sufficiently close together a quantum coherent phase of interlayer excitons emerges at low temperature [1]. Although the condensed phase itself is qualitatively well understood, the nature of the transition remains somewhat mysterious. In the absence of a detailed understanding of the transition, it is often assumed that the transition is a first order one and that at layer separations just above the critical one the system may be regarded as two completely decoupled composite fermion (CF) metals.

Using a combination of interlayer tunneling and conventional transport, we find that the model of decoupled CF metals is not a good quantitative description of the incoherent phase just above the critical layer separation. Interlayer Coulomb interactions are not negligible and appear to renormalize downward the CF Fermi energy to a significant degree. Moreover, the tunneling process itself is substantially modified by these same interactions, including its dependence on the spin polarization of the system.

## Reference

[1] J. P. Eisenstein. Annual Review of Condensed Matter Physics, **5**, 159 (2014).

# Topological Excitonic Condensation and Beyond in Double Quantum Wells

Rui-Rui Du

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Electron-hole pairing can occur in a dilute semimetal, transforming the system into an excitonic insulator state in which a gap spontaneously appears at the Fermi surface, analogous to a Bardeen-Cooper-Schrieffer (BCS) superconductor. In this talk I will report optical spectroscopic and electronic transport evidence for the formation of an excitonic insulator gap in an inverted InAs/GaSb quantum-well (QW) system at low temperatures and dilute electron ($n$) – hole ($p$) densities [1]. Terahertz transmission spectra exhibit two absorption lines that are quantitatively consistent with predictions from the pair-breaking excitation dispersion calculated based on the BCS gap equation. Low-temperature electronic transport measurements reveal a gap of ≈25 K with a critical temperature of ≈10 K in the bulk, together with quantized edge conductance, suggesting the occurrence of a topological excitonic insulator phase. We will also mention the transport properties of the edge states, which suggest the formation of a novel helical Luttinger liquid [2]. In recent experiments using InAs/InGaSb double QWs with a thin tunneling barrier, we have observed a number of insulating states where a charge-unbalanced state ($p >> n$) was observed in addition to the charge neutral state ($p \sim n$). We found that these bulk insulating states are lack of edge conductance, consistent with the notion that by tuning the inter-layer tunneling, a topological phase transition could take place in the exciton binding energy verses tunneling phase diagram, as proposed by Refs. [3,4].

## References

[1] L. Du *et al*. *Evidence for a topological excitonic insulator in InAs/GaSb bilayers*. Nature Communications **8**, 1971 (2017).

[2] T. Li *et al*. *Observation of a Helical Luttinger Liquid in InAs/GaSb Quantum Spin Hall Edges*. Physical Review Letters **115**, 136804 (2015).

[3] D. I. Pikulin, T. Hyart. *Interplay of exciton condensation and quantum spin Hall effect in InAs/GaSb bilayers*. Physical Review Letters **112**, 176403 (2014).

[4] F. Xue, A.H. MacDonald. *Time-Reversal Symmetry-Breaking Nematic Insulators near Quantum Spin Hall Phase Transitions*. Physical Review Letters **120**, 186802 (2018).

# Interlayer Excitons and Magneto-Exciton Condensation in van der Waals Heterostructures

Philip Kim

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A pair of electron and hole across the interface of semiconductor heterostructure can form a bound quantum state of the interlayer exciton. In a coupled interface between atomically thin van der Waals layers, the Coulomb interaction of the interlayer exciton increases further. Coulomb drag effect is a mesoscopic effect which manifests many-body interactions between two low-dimensional systems, which has served an extremely useful probe the strong correlation in quantum systems [1]. In this presentation, we will first discuss observing interlayer exciton formation in semiconducting transition metal dichalcogenide (TMDC) layers. Unlike conventional semiconductor heterostructures, charge transport in of the devices is found to critically depend on the interlayer charge transport, electron-hole recombination process mediated by tunnelling across the interface. We demonstrate the enhanced electronic, optoelectronic performances in the vdW heterostructures, tuned by applying gate voltages, suggesting that these a few atom thick interfaces may provide a fundamental platform to realize novel physical phenomena. In addition, spatially confined quantum structures in TMDC can offer unique valley-spin features, holding the promises for novel mesoscopic systems, such as valley-spin qubits. In the second part of the presentation, we will discuss magneto-exciton condensation. In this electronic double layer subject to strong magnetic fields, filled Landau states in one-layer bind with empty states of the other layer to form an exciton condensate. Driving current in one graphene layer generates a near-quantized Hall voltage in the other layer, resulting in coherent exciton transport. In our experiment, capitalizing strong Coulomb interaction across the atomically thin hBN separation layer, we realize a superfluid condensation of magnetic-field-induced excitons. For small magnetic fields (the BEC limit), the counter-flow resistance shows an activation behaviour. On the contrary, for large magnetic fields limit where the inter-exciton separation decreases (the BCS limit), the counter-flow resistance exhibits sharp transitions in temperature showing characters of Berezinskii-Kosterlitz-Thouless (BKT) transition. Furthermore, complete experimental control of density, displacement and magnetic fields in our graphene double layer system enables us to explore the rich phase diagram of several superfluid exciton phases with the different internal quantum degrees of freedom.

## Reference

[1] H. Rubel, A. Fischer, W. Dietsche, K. von Klitzing, K. Eberl. Physical Review Letters **78**, 1763 (1997).

# Moiré superlattices and magnetic minibands in graphene heterostructures

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When graphene lattice is aligned with the hBN lattice, a long-wavelength periodic moiré pattern forms due to a weak incommensurability of the two lattice structures, leading to a long-range superlattice affecting properties of electrons in graphene, including formation of miniband spectra for Dirac electrons [1–3] and reappearance of magnetic minibands [4,5] at the rational values of magnetic field flux through the supercell area (in units of $\phi_0 = h/e$), also known as Hofstadter butterfly [6].

Here, we show that the quantum effect of the minibands formation in long-period moiré superlattices (mSL) in graphene/hBN heterostructures affect their transport measurements up to the room temperature. In relation to the low-field behavior, we find that the overall temperature dependence of resistivity displays the opening in a new scattering process: the umklapp electron-electron scattering in which two electrons coherently transfer the mSL Bragg momentum to the crystal [7]. The formation magnetic minbands and their manifestation in magneto-oscillation of the diagonal conductivity tensor persist up to the room temperature [8], too, with full hierarchy of features that are attributed to the rational flux values $\phi = (p/q)\phi_0$, with $p = 1$, 2 and up to 3 (and $7 < q < 1$), now, observed [9] at the intermediate range of 50 K < $T$ < 200K.

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# Double Bilayer Graphene Excitonic Superfluids

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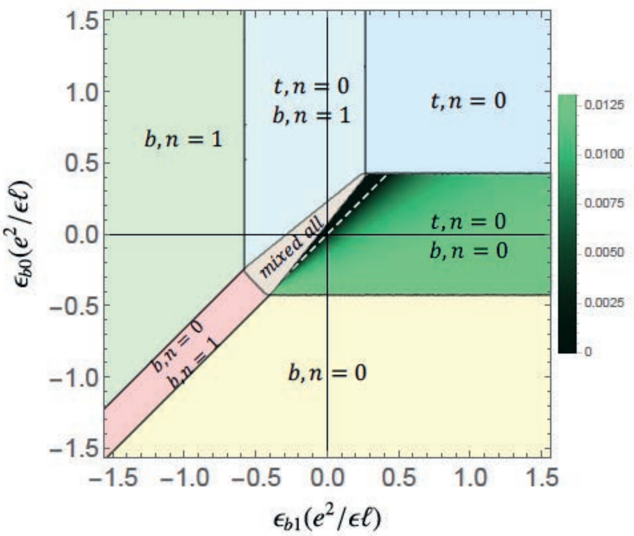
The excitonic superfluid, which is characterized by spontaneous coherence between electrons in two-different layers, is one of the most interesting broken symmetry states in the quantum Hall regime. In this talk I will discuss how the extra orbital degree-of-freedom of the $N = 0$ Landau level of bilayer graphene enriches excitonic superfluidity, as it enriches many other aspects of the fractional quantum Hall effect. The most interesting property is summarized in the phase diagram at left which summarizes how the state depend on the orbital $n = 0$ and $n = 1$ energies in the bottom layer relative to the $n = 0$ energy of the top layer. The exciton condensate state occurs in the green region of the phase diagram where the $n = 0$ states are close to degeneracy in the two layers, and the shade of green indicates the superfluid density, i.e. the capacity to carry counterflow supercurrents, of the excitonic state. (See the color scale on the right hand side.) We [1] have found that the superfluid density approaches zero as the $n = 0$ and $n = 1$ in the bottom layer approach degeneracy, and that long-wave length density wave states occur when the $n = 1$ state is slightly lower in energy. I will explain why this behaviour occurs and discuss its implications for counterflow transport.

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# Quantization of heat flow in the FQHE regime

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Quantum mechanics sets an upper bound on the amount of charge flow as well as on the amount of heat flow in ballistic one-dimensional channels. The two relevant upper bounds, which combine only fundamental constants, are the quantum of the **electrical** conductance $G_e = e^2/h$, and the quantum of the **thermal** conductance $G_{th} = \kappa_0 T = (\pi^2 k_B^2/3h)T$ – $e$ electron charge, $h$ Planck's constant, $k_B$ Boltzmann's constant, $T$ temperature. Remarkably, the latter does not depend on particles' charge or their exchange statistics, and, moreover, it is expected to be insensitive to the interaction strength among the particles. Yet, unlike the relative ease in observing the quantization of the electrical conductance, measuring (relatively) accurately the thermal conductance is more challenging.

The quantization of $G_{th}$ in 1D ballistic channels was demonstrated for weakly interacting particles: phonons [1], photons [2], and an electronic Fermi-liquid [3]. I will describe our recent experiments with heat flow in chiral edge modes in a strongly interacting system of 2D electrons in the fractional quantum Hall regime. In the lowest Landau level we studied particle states (filling factor, $\nu < ½$) and the more complex hole-conjugate states ($½ < \nu < 1$), with the latter carrying counter-propagating chiral modes: *downstream* charge and *upstream* neutral [4]. We verified the quantization of $G_{th}$ of the charged as well as of the neutral chiral edge modes. In the first-excited Landau level ($2 < \nu < 3$), we studied the main fractional states, $\nu = 7/3$, $5/2$, $8/3$. Concentrating on the even-denominator $\nu = 5/2$ state, we found fractional quantization of the thermal conductance $G_{th} = (2+½)\kappa_0 T$, providing a definite mark of a non-abelian nature of the $\nu = 5/2$ state, harboring the sought after Majorana excitations [5].

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# Chiral 1D transport in magnetic topological insulators: precise quantization and manipulation

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The quantum anomalous Hall effect in thin film magnetic topological insulators (MTIs) is characterized by chiral, one-dimensional conduction along the film edges when the sample is uniformly magnetized. This has been experimentally confirmed by measurements of quantized Hall resistance and near-vanishing longitudinal resistivity in magnetically doped $(Bi,Sb)_2Te_3$. I will describe two recent advances: 1. We have measured quantized Hall resistance in absence of an external magnetic field to precision and accuracy better than one part per million, and longitudinal resistivity below 10 mΩ, using techniques developed for quantum Hall metrology. We have also achieved some insight into the nature of residual dissipation. 2. Chiral conduction is expected not only along film edges but also along magnetic domain walls. Clear detection of these modes in MTIs has until recently proved challenging. We have intentionally created magnetic domain walls in an MTI, and study electrical transport along those domain walls. In agreement with theoretical predictions, we observe chiral transport along domain walls. I will also describe evidence that two modes equilibrate while co-propagating along the length of the domain wall.

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# Probing the Bulk and Edge States in InAs-based Heterostructures

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Heterostructures containing InAs are attracting increasing interest, as they possess strong spin-orbit interaction and allow for good interface with superconductors, key ingredients for engineering topological phases [1,2]. In order to exploit exotic quasiparticles anticipated to emerge at the edge of such systems, understanding and controlling the electronic states near the sample edge is of great importance. In particular, in InAs the Fermi-level pinning at the mesa edge may render the local electron density near the edge higher than the bulk value. At high fields, this leads to the formation of additional edge channels, which carry current in the opposite direction and may result in the breakdown of the quantum Hall effect (QHE) [3]. The edge potential of InAs can also lead to trivial edge conduction at zero field in InAs/GaSb quantum spin Hall insulators [4,5] and InAs quantum wells [5,6].

Here we report transport measurements on InAs/$Al_{0.7}Ga_{0.3}Sb$ quantum wells in the quantum Hall regime and show how the edge properties affect the QHE. In contrast to the report in Ref. [3], where the counter-flowing edge channels appeared only when a negative gate voltage below a threshold was applied, we find that they can be present in more general conditions of both positive and negative gate voltages and even in samples without a front gate. We determined the transmission probability of counter-flowing edge channels using samples with different edge lengths and studied how it varies with the edge length, filling factor, and magnetic field. Analysis using the Landauer-Büttiker model with counter-flowing edge channels [3,7] shows that the transmission probability decreases exponentially as a function of edge ledge, with a characteristic decay length of 70 µm at filling factor of $\nu = 4$ and magnetic field of 6 T. The decay length becomes even longer with increasing magnetic field. Our results suggest that the presence of QHE does not necessary imply the absence of counter-flowing edge channels, so care must be exerted in discussing the edge physics even when the QHE is fully developed. In the presentation, we also report capacitance measurements which provide complementary information on the bulk states not accessible through transport measurements.

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# Momentum, Energy, and Spin Resolved Tunneling of Quantum Hall States

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The single-particle spectral function measures the density of electronic states (DOS) in a material as a function of both momentum and energy, providing central insights into phenomena such as superconductivity and Mott insulators. While scanning tunneling microscopy (STM) and other tunneling methods have provided partial spectral information, until now only angle-resolved photoemission spectroscopy (ARPES) has permitted a comprehensive determination of the spectral function of materials in both momentum and energy. However, ARPES operates only on electronic systems at the material surface and cannot work in the presence of applied magnetic fields. Using pulsed tunneling methods [1] we have previously demonstrated precision and high resolution tunneling spectra of the 2D electronic system (2DES). The extremely high resolution of these measurements allowed the discovery of a delicate resonance that arises from coupling of a tunneling electron to phonons of a Wigner Crystal [2].

Here, we demonstrate a new pulsed tunneling method (MERTS) for determining the full momentum and energy resolved electronic spectral function of a 2DES embedded in a semiconductor [3]. The technique remains operational in the presence of large externally applied magnetic fields and functions even for electronic systems with zero electrical conductivity or with zero electron density. MERTS provides a direct high-resolution and high-fidelity probe of the dispersion and dynamics of the interacting 2D electron system. Using this technique, we uncover signatures of many-body effects involving electron-phonon interactions, plasmons, polarons with unprecedented resolution. When a perpendicular magnetic field is applied, the spectra evolve into discrete Landau levels. The massively degenerate electronic states strongly interact with nearly dispersionless LO-phonons and give rise to a novel phonon analog of the vacuum Rabi splitting in atomic systems. I will discuss how this technique will be instrumental to probe emergent quantum phases in the quantum Hall limit, such as stripe, bubble phases, and fractional quantum Hall states.

We have also extended the pulsed tunneling method to probe the spin polarization of both the ground and the excited states of quantum Hall systems. Employing a bilayer magnetic tunnel junction consisting of one fully spin-polarized layer and another layer with tunable filling factor, we measured the filling factor dependence of spin-polarized currents flowing between the two layers. Our data show an oscillating pattern of the spin-polarized currents. In particular, the drastic decrease of the spin-polarized current near $\nu = 1$ is consistent with the formation of skyrmions. In prior experiments, we discovered high energy "sash" features arising from two-body Haldane pseudopotentials [4]. We can now perform spin-selective tunneling to determine the spin structure of the Haldane sash features, providing a key measurement for describing the strong electronic correlations in quantum Hall systems. Finally, At the time of the writing of this abstract, we have developed new samples showing strong $\nu = 5/2$ features in capacitance., and we are working to measure spin polarization of the 5/2 state. The talk will describe our latest results on the spin polarization of the 5/2 state and other fractional quantum Hall states.

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# Exploring Magnonic Excitation in Quantum Hall Ferromagnets

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Spin waves are essential to understanding the intrinsic ordering and thermodynamic properties of magnetic systems. An attractive candidate for studying long-lived spin-wave physics is the quantum Hall (QH) ferromagnet, which forms spontaneously in clean two-dimensional electron systems at low temperature and in a perpendicular magnetic field. However, the charge-neutral nature of these elementary spin excitations has made them challenging to detect and study. Here we use out-of-equilibrium occupation of QH edge channels in graphene to excite and detect spin waves in magnetically ordered QH states. Our experiments provide direct evidence for long distance spin wave propagation through different ferromagnetic phases in the $N = 0$ Landau level (LL), as well as across the insulating canted antiferromagnetic (CAF) phase. Our results open a new arena of experimental investigation into the fundamental magnetic properties of these exotic two-dimensional electron systems.

# New progress in quantum anomalous Hall effect

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The quantum anomalous Hall (QAH) effect is a quantum Hall effect induced by spontaneous magnetization, and occurs in two-dimensional insulators with topologically nontrivial electronic band structure which is characterized by a non-zero Chern number. It was first experimentally observed in the thin films of magnetically doped $(Bi,Sb)_2Te_3$ topological insulators (TIs) in 2013, more than thirty years after the discovery of the first quantum Hall effect by Klaus von Klitzing. In this talk, I will report on some recent experimental progresses in this direction. By co-doping of Cr and V into $(Bi,Sb)_2Te_3$ TI films, we are able to significantly increase the observation temperature of QAH effect. More interestingly, we can construct other topological states of matter such as axion insulator, quantum spin Hall insulator and QAH insulator of high Chern number by growing QAH insulator-based heterostructures.

# Topological Phenomena and Anomaly in Graphene

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The electron motion in graphene, first fabricated by mechanical exfoliation method and later by various other methods, is governed by Weyl's equation for a neutrino or the Dirac equation with vanishing rest mass. The pseudo-spin is quantized into the direction of the electron motion and the wave function exhibits a sign change due to Berry's phase when the wave vector $\boldsymbol{k}$ is rotated around the origin and therefore has a topological singularity at $\boldsymbol{k} = 0$. This singularity is the origin of the peculiar behavior in transport properties of graphene, such as the minimum conductivity at zero energy, the half-integer quantum Hall effect, the dynamical conductivity, crossover between weak-and anti-localization, and a very singular diamagnetic response. Various reviews have already been published [1–4].

In this talk, exotic electronic and transport properties of graphene are reviewed from a theoretical point of view. The subjects include the minimum conductivity at the Dirac point [5,6], the weak-field Hall effect [7,8], origin of the singular diamagnetism [9–11], the topological valley-Hall conductivity in mono- and bi-layer graphenes with gap [12–14], and the weak-field magnetoresistance. Similar singularities appear in various two-dimensional systems such as those with giant Rashba spin-orbit interaction [15–17] and in phosphorene, which will be discussed if the time allows.

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# Progress toward quantitative understanding of the fractional quantum Hall effect

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While we have a secure understanding of the underlying physics of the FQHE, a quantitative comparison with experiment is often not as accurate as one would have anticipated. I will report on our work [1,2] that treats the effect of Landau level mixing in a fixed-phase diffusion Monte Carlo method, giving insight into certain old experimental puzzles. In particular, we explain why the spin phase transitions for FQH sate in the vicinity of 1/2 behave differently than those in the vicinity of 3/2. We also explain and why the insulating phase in p-doped GaAs systems appears in the vicinity of $\nu = 1/3$, in contrast to the *n*-doped systems where it appears only near $\nu = 1/5$. If time permits, I will make a remark on a new perspective into the phenomenology of the FQHE in the second Landau level [3].

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# Quantum mechanical shift current

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We discuss a novel manifestation of quantum mechanical current flow in solids upon photoexcitation. From old days, bulk photovoltaic effect has been known to exist in non-centrosymmetric crystals such as poled ferroelectrics [1]. Naive explanation was that the drift current flows due to electric field uncompensated by insufficient formation of electric double layer on the surfaces of polar crystals. Now, it is proposed and confirmed that a quantum mechanical effect, described by the Berry's connection of Floquet bands, drives photocurrent called "shift current" as a second order process [2,3]. We present experimental observations of photovoltaic effect in such polar materials systems as $LaFeO_3/SrTiO_3$ interfaces [4], a ferroelectric organic TTF-CA [5], and a polar semiconductor SbSI [6]. Ultrafast THz spectroscopy [7] and device physics [8] studies have elucidated interesting features of the shift current.

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# Resistively-Detected Nuclear-Magnetic-Resonance in Microscopic Scale

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Current-induced dynamic nuclear polarization (DNP) has been achieved by using the current flow in a quantum Hall ferromagnet [1], edge-channel tunnelling [2], and quantum Hall breakdown [3]. They are connected to highly-sensitive resistively-detected nuclear-magnetic-resonance (RDNMR), which is widely applied to clarify physics in semiconductor quantum systems [4]. In particular, the Knight shift in NMR spectra provides quantitative information on electron spin polarization in quantum systems [5]. The key role played by the chiral nature of the edge channel in DNP is also confirmed for RDNMR at $\nu = 2$ quantum Hall ferromagnet [6].

Recently, we combined RDNMR with a sophisticated scanning nanoprobe system operating at dilution temperatures for microscopic imaging of the RDNMR signal. Electric quadrupolar coupling enables us to manipulate nuclear spins by using the RF electric field in place of the RF magnetic field. In addition, double-frequency resonance is a powerful means of detecting small nuclear-related signals without background noise [7]. As an example of an interesting application of this measurement, we have demonstrated both intensity and Knight shift mappings of RDNMR signals for quantum Hall breakdown near $\nu = 1$ [8]. The obtained results reveal the microscopic origin of the nonequilibrium quantum Hall phenomena, and highlight the potential use of our technique in novel microscopic studies of semiconductor quantum systems.

The RDNMR can be also applied to study the characteristics of microscopically confined systems. Here, we use a triple-gate quantum-point-contact (QPC) where we have a center gate in addition to the split Schottky gate for the confinement of an electron channel. The RDNMR in QPC has been achieved by setting the filling factor outside and inside of QPC at even and odd numbers, respectively. Nuclear polarization and successful RDNMR inside the QPC have been confirmed by the Knight shift in the obtained spectrum [9]. It is noteworthy that the RDNMR signal of QPC can be detected even at very low magnetic fields less than 1 T [10]. This result encourages us to study electronic states in the QPC near zero magnetic field by using the RDNMR technique. Furthermore, RDNMR quadrupolar splitting directly reflects strain at the measuring point. RDNMR measurements with various gate voltage parameters of the QPC demonstrate that flowing electrons feel different strain when the channel position is shifted in the nanometer scale in the QPC [11].

In conclusion, RDNMR and its application to magnetic-resonance-imaging have become a powerful tool to microscopically study electronic behaviour, spin physics, and strain distribution in semiconductor quantum systems.

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# Nemantic Phases in 2D Electron Systems: Role of Mass Anisotropy and Magnetization

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There is a close competition between the many-body ground states in a high-mobility two-dimensional electron system (2DES) when the Fermi energy lies in a half-filled Landau level with high orbital index. The compressible phases or the incompressible fractional quantum Hall states, which are isotropic, are typically replaced by broken-symmetry, stripe-like (nematic) phases where the charge density oscillates along one direction. These are manifested by highly-anisotropic, in-plane transport coefficients, with much higher resistance along the direction of charge oscillations. In this talk we will discuss our recent observations of highly anisotropic states in two unusual, high-quality 2DESs confined to AlAs quantum wells [1].

In one system, the 2D electrons are confined to a very narrow AlAs quantum well (width < 6 nm) and occupy the out-of-plane valley, meaning the in-plane effective mas is *isotropic*. In this system we tune the magnetization of the 2DES by tilting the sample in the magnetic field. We show the unexpected result that in an interacting 2DES, the robustness of the nematic phase, which represents an order in the charge degree of freedom, not only depends on the orbital index of the topmost, half-filled Landau level, but it is also strongly correlated with the *magnetic order* of the system [2]. Intriguingly, when the system is fully magnetized, the nematic phase is particularly robust and persists to much higher temperatures compared to the nematic phases observed previously in quantum Hall systems. Our results give fundamental new insight into the role of magnetization in stabilizing the nematic phase, while also providing a new knob with which it can be effectively tuned.

In a second system, we confine the 2D electrons in wide AlAs quantum wells where they occupy two in-plane valleys with highly *anisotropic* effective masses. Here we induce the anisotropic phases not by tilting the sample but rather via applying uniaxial, in-plane strain to place all the 2D electrons in one anisotropic valley. At a half-filled Landau level, we observe a very unusual phase whose in-plane resistances are highly anisotropic and yet the Hall resistance is well-quantized at low temperatures [3].

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# Competing Fractional Quantum Hall and Nematic Phases in the Half-filled Second Landau Level

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After almost four decades from the discovery of the integer quantum Hall effect [1], the two-dimensional electron gas in strong magnetic fields continues to provide rich and surprising physics. One focus of current interest is the behavior of this system at half-filled Landau levels. The ordered ground state at a given half filling was reported to be either a fractional quantum Hall state [2] or a nematic phase [3,4]. However, the presence of both of these ordered phases and therefore a transition between them did not seem possible in the absence of externally applied symmetry breaking fields favoring the nematic. This state of affairs has changed recently with the observation a pressure-driven quantum phase transition between the $\nu = 5/2$ fractional quantum Hall state and the nematic phase [5]. In this talk we provide evidence of a similar quantum phase transition at filling factor $\nu = 7/2$ and we discuss the role of the hydrostatic pressure in driving the transition. The fractional quantum Hall states at $\nu = 5/2$ and $\nu = 7/2$ involved in the transition are due to pairing of composite fermions. We thus found that the competition of pairing and nematicity present in various condensed matter systems also occurs in the two-dimensional electron gas tuned to the half-filled second Landau level.

This work is supported by the US DOE grant DE-SC0006671.

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# Open questions about a Landau level near half-filling

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I will review some outstanding questions related to particle-hole symmetry in quantum Hall systems with a half-filled highest Landau level. For spin-polarized electrons with two-body interactions, in the limit where one can neglect Landau-level mixing, there should be an exact particle-hole symmetry between systems with Landau-level filling fractions $f$ and 1-$f$. For total filling $\nu = 1/2$, which is $f = 1/2$ in the lowest Landau level, where experiments find a compressible state without a quantized Hall conductance, one does not expect to find broken particle-hole symmetry. A recent theory of this state, introduced by D. T. Son [1], which uses Dirac composite fermions, is explicitly particle-hole symmetric, as it assumes particle-hole symmetry from the beginning. By contrast, the traditional description, based on non-relativistic composite fermions interacting with a Chern-Simons gauge field, is not explicitly particle-hole symmetric, but it makes equivalent predictions to the Son-Dirac theory for almost all physical quantities in the limit of a half-filled Landau level [2]. The questions, here, are whether remaining differences in the theories are reconcilable, and if so, how is particle-hole symmetry completely restored in the traditional theory?

In the second Landau level, at filling $\nu = 5/2$, it has long been believed, based on numerical calculations, that particle-hole symmetry should be spontaneously broken, and that the system should choose either a "Pfaffian" state, or its inequivalent particle-hole conjugate, the "Anti-Pfaffian". These states are topologically distinct, with edge states that have conformal central charges $K$=7/2 and $K$=3/2, respectively. However, recent measurements of the quantized thermal Hall conductance by the Weizmann group [3] point to a value $K = 5/2$, which one might expect for a particle-hole symmetric ground state, in disagreement with previous expectations. We have investigated the possibility that an inhomogeneous mixture could explain the discrepancy [4].

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# Nanoscale thermal imaging Glimpse into dissipation in quantum systems

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Energy dissipation is a fundamental process governing the dynamics of classical and quantum systems. Despite its vital importance, direct imaging and microscopy of dissipation in quantum systems is currently impossible because the existing thermal imaging methods lack the necessary sensitivity and are unsuitable for low temperature operation. We developed a scanning nanoSQUID that resides at the apex of a sharp pipette acting simultaneously as nanomagnetometer with single spin sensitivity [1] and as nanothermometer providing cryogenic thermal imaging with four orders of magnitude improved thermal sensitivity of below 1 μK [2]. The non-contact non-invasive thermometry allows thermal imaging of minute energy dissipation down to the level equivalent to the fundamental Landauer limit for continuous readout of a single qubit. These advances enable observation of changes in dissipation due to single electron charging of a quantum dot and visualization and control of heat generated by electrons scattering off a single atomic defect in graphene [3], opening the door to direct imaging and spectroscopy of dissipation processes and magneto-electric effects in quantum Hall states.

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# Using Topology to Build a Better Qubit

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This talk will describe an adventure currently underway to coax into existence excitations (particles) that have non-Abelian braiding statistics – something yet unseen in the physical world – and to not stop there, but to try to employ these new excitations, Majorana zero modes, for a topological quantum computing. Which is more challenging: the mathematics of computing by braiding particles? The material science of creating hybrid materials that support Majorana modes? The nanotechnology of fabricating the devices? The condensed matter physics of producing them in the lab? The electrical engineering of controlling and reading out their state? The software to control the electronics on sub-microsecond timescales? This talk will try to cover a small amount of each of these aspects, to convey the sense of complexity of quantum computing generally. Research supported by Microsoft and the Danish National Research Foundation.

# Abstracts of Posters

# POSTERS

# Universality of the Fermi surface properties of the ground state for the half-filled Landau level and other interacting two-dimensional Dirac fermions

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The role of electron-electron interactions in two-dimensional Dirac fermion systems remains enigmatic. Using a combination of non-perturbative numerical and analytical techniques that incorporate both the contact and long-range parts of the Coulomb interaction, we identify the two previously discussed regimes: a Gross-Neveu transition to a strongly correlated Mott insulator, and a semi-metallic state with a logarithmically diverging Fermi velocity accurately described by the random phase approximation. We demonstrate [1] that experimental realizations of Dirac fermions span this crossover, and make predictions that can readily be tested with current experimental capabilities. Applying these ideas to the study of Dirac fermions believed to emerge [2] in the Quantum Hall liquid for the $\nu = 1/2$ Landau level, we demonstrate using various analytical techniques (perturbation theory, Hartree-Fock, Random-Phase-Approximation) and non-perturbative numerical techniques (projective quantum Monte Carlo) that there is a universal decrease in the Fermi-surface anisotropy for such Dirac fermions [3]. In light of recent experimental work [4] on the $\nu = 1/2$ Landau level, our work is strongly suggestive that Dirac fermions are indeed the underlying excitations of the emergent Fermi liquid ground state for the half-filled Landau level. We make further predictions that can be tested experimentally.

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Poster 2

# Quantum Wires defined by Cleaved Edge Overgrowth – Challenges & Future Goals

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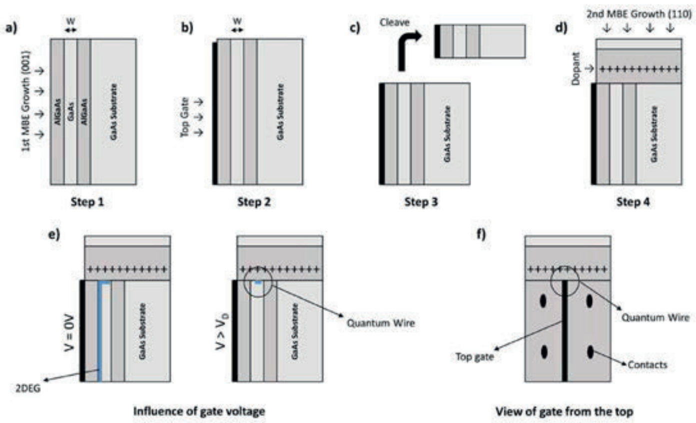
We investigate the one dimensional (1D) physics of Cleaved Edge Overgrowth (CEO) quantum wires (QWRs) using AlGaAs/GaAs Molecular Beam Epitaxy (MBE). These very pure and atomically precise quantum systems are expected to reveal new physics of 1D Luttinger Liquids. Especially we are interested in the creation of separately gatable coupled QWRs and experiments inducing topological superconductivity in a wire due to the proximity effect and the influence of a magnetic field.

**Experimental Realisation**

The concept of a quantum wire fabrication using the CEO technique on a 2DEG is shown in Fig. 1. We start with a AlGaAs/GaAs heterostruture growth along the (001) direction (Fig. 1a). Then we define top gate structures on top of our sample by standard optical lithography and metal deposition (Fig. 1b), before we reintroduce the sample into the MBE chamber. The sample is cleaved along the (110) direction (Fig. 1c) in the ultra high vacuum environment of the MBE chamber, followed by a second MBE growth along the cleaved (110) plane (Fig. 1d).




Thus we can grow heterostructures along two crystal directions without contaminating the interface in between. The quantum wire forms at the interface between the heterostructures by gate depletion of the 2DEG (Fig. 1e). The length of the quantum wire is given by the width of the top gate. The 2DEG is contacted on each side of the gate, which allows for four-terminal transport measurements. Alternatively to the top gates explained above different approaches have been studied in order to deplete the wire. Back gates created by oxygen ion implantation [1], in-situ grown p-type top gates and shadow mask deposited top gates are currently under investigation.

**Experimental Applications**

Our first goal is to build a wire in an high mobility AlGaAs/GaAs system. Once this is achieved the development of separately gateable AlGaAs/GaAs quantum wires will be of interest. Within the first MBE growth illustrated in Fig. 1, a second AlGaAs/GaAs/AlGaAs stack will be grown. This will create a second wire which will be gated using structured back gates created by oxygen ion implantation [1]. With this setup the coupling between two separately tuned wires can be studied and Coulomb drag can be seen. For stronger spin-orbit interactions, InAs wires would also be of interest in the future.

Another future project is the creation of a topological superconducting state. The basic setup needed is a 1D wire with spin-orbit coupling, a s-wave superconductor deposited on the cleaved edge and a magnetic field to break time-reversal symmetry [2]. Near the ends of the wire at the interface between the topological superconducting state and the trivial state, Majorana Fermions are predicted [3].

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# Precision measurements of 1 MΩ quantized Hall array resistance plateau

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The realization of invariant physical quantities directly traceable to the fundamental constants is the spirit of the new International System of Units (SI), which is effective as of 2019. The lack of an accurate and ideal high resistance prohibits the realization of the new SI ampere based on single-electron source. A quantum mechanical high resistor would be also a key element bridging the single-electron current source and the Josephson voltage standard for the trilateral comparison in the quantum metrology triangle experiment. Here, we report a direct precision comparison between the 1 MΩ quantized Hall array resistance (QHAR) made of GaAs/AlGaAs heterostructure and the quantum Hall resistance (QHR) standard with a cryogenic current comparator resistance bridge at the ultimate precision (relative measurement uncertainty of $17{\cdot}10^{-9}$ at the 95% confidence level). Robustness tests of the quantization in the array including thermal cycles and other operational parameters including the temperature, magnetic field, and applied current demonstrate the invariant nature of the combined array Hall resistance within measurement uncertainty as well as the potential for a genuine current-to-voltage converter for small current measurements. Finally, the associated uncertainty budget and the origin of the measured deviation from a designed value are discussed.

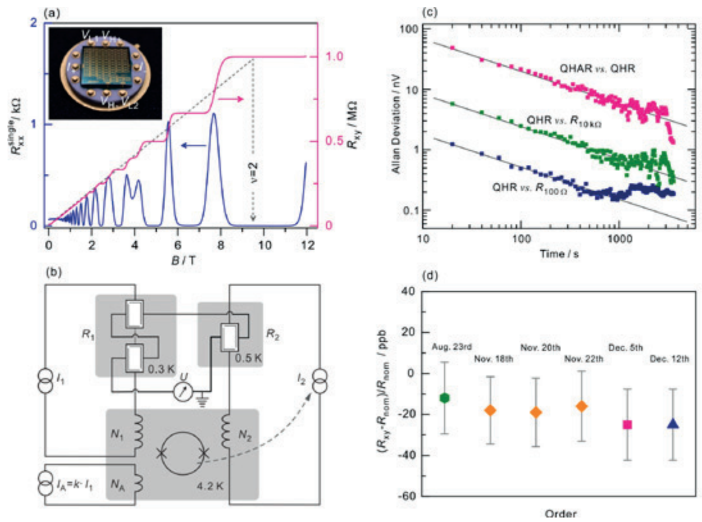


**Fig. 1:** (a) Magnetic field dependence of the combined Hall resistance of the array and longitudinal resistance of a single Hall unit at 0.3 K. (b) Schematic diagram of the cryogenic current comparator resistance bridge for a direct comparison of the QHAR and the QHR standard. (c) Allan deviations of the bridge voltage difference data sets. (d) Stability of the thermally cycled QHR array.

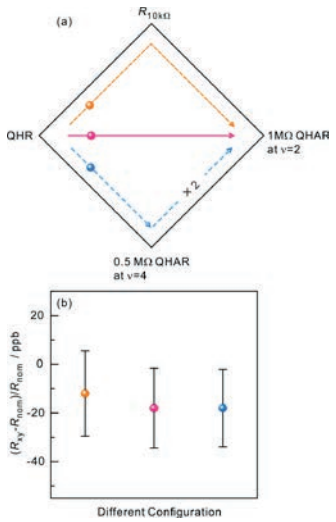


**Fig. 2:** (a) Determination of the QHAR at a base temperature of 0.3 K at filling factor 2 via three different ways. (b) Summary of three different results coded by the corresponding coloured spheres in (a).

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Poster 4

# Dynamic domain structure in the microwave-induced zero-resistance states

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The zero-resistance states (ZRSs) [1] develop in minima of the microwave induced magnetoresistance oscillations [2]. They show up in tending to zero magnetoresistance in the Hall bar geometry and magnetoconductance in the Corbino geometry of high-quality two-dimensional electron systems. Their appearance is attributed [3] to the formation of a static domain structure produced by a spontaneous dc electric field with different orientations in different domains. The origin of such spontaneous symmetry breaking is a negative dissipative conductivity resulting from the microwave radiation. This scenario implies equal probabilities for opposite electric field orientations in each domain. In principle, the detection of a microwave-induced photo-voltage between an internal point of a sample mesa and a point on its perimeter could signal the formation of a domain structure. However, it appeared that there is another mechanism which can cause the microwave photo-voltage oscillating relative to the zero level as a function of the $2\pi f/\omega_c$ ratio [4]. Here $f$ is the microwave frequency and $\omega_c$ is the cyclotron frequency. The observation [5] of the microwave photo-voltage signal switching in time between two levels synchronously on different pairs of contacts distributed over the sample mesa which occurs under nominally stationary experimental conditions was the first convincing manifestation of the spontaneous electric field. In contrast to the oscillating photo-voltage this effect is present in ZRSs only. Although the observed non-stationary voltage showed different time dependences, from periodic self-oscillations to rather irregular switching, in most cases the quasi-periodic switching was observed. Further studies [6] showed that the essence of the switching effect is a reversal of a spontaneous electric field in the domains. Such a behavior in principle could be inherent for the spontaneous symmetry breaking leading to the formation of the domain structure. However, its quasi-periodic behavior is inconsistent with the fluctuation origin and implies the existence of a characteristic time scale. It has been argued [7] that the quasi-periodic switching can be caused by the redistribution of charges in the doping layer supplying electrons to the two-dimensional system. This redistribution is the response of the layer on the spontaneous electric field in the domains. The characteristic time of the redistribution is inversely proportional to the conductivity of the doping layer.

On samples produced from the same wafer, we have measured the temperature dependences of the doping layer conductivity and of the average switching frequency [8]. We have found that both quantities follow the thermoactivation law with close values of the activation energy. This observation strongly supports the explanation of the domain dynamics in terms of the domain field screening by the charges in the doping layer and completes the qualitative picture of the dynamic domain structure.

Our data also imply a possible freezing of the domain structure in one of the electric field configurations, i.e., a transition to a static domain structure. The authors acknowledge support from RNF, Grant No. 14-12-00599 (S.I.D.) and from the GIF (J.H.S. and V.U.).

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# Light induced Hall effect in a doped monolayer semiconductor

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Optoelectronic properties of two-dimensional (2D) transition metal dichalcogenides (TMDs) are of great interest since the band gap of these materials corresponds to the visible range of the electromagnetic spectrum. For instance, in molybdenum disulphide ($MoS_2$) – a 2D semiconductor TMD the band gap energy is about 2 eV in monolayers. Monolayer $MoS_2$ has a non-centrosymmertic crystal, inherent broken inversion symmetry which leads to a large spin-orbit interaction (SOC). The SOC splits the valence band by 160 meV and gives rise to strong excitonic transitions due to the direct band gap at low energy K and –K valleys. The broken inversion symmetry together with time reversal symmetry is responsible for spin-valley coupling in monolayer $MoS_2$ and similar TMDs. As a result, when monolayer $MoS_2$ phototransistors are illuminated by circularly polarized light which preferentially excites electrons into a specific valley it is possible to observe both longitudinal photocurrent and transverse (Hall) photovoltage. The longitudinal dichroic photocurrent is due to the circular photogalvanic effect and it depends on the state of circular polarization, the angle of incidence, and the photon energy [1]. The Hall photovoltage can be observed in normal incidence, in the absence of a magnetic field, and its sign depends on the valley index which can be controlled by circularly polarized light state [2]. Here, we present magnetic field dependence of the Hall photovoltage of monolayer $MoS_2$ doped with a magnetic element and comment on our results.

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# Drag Experiments in Double Bilayer Graphene

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We performed drag experiments in double bilayer graphene heterostructures, where two sheets of bilayer graphene were separated by a few nanometer thick barrier of hexagonal boron nitride. Carrier mobilities in both layer range from μ = 40 000 cm$^2$/Vs to 80 000 cm$^2$/Vs.

At *T* = 1.4 K, drag effects are very weak, but at elevated temperatures, pronounced drag signals appear. At *B* = 0 T, or low magnetic fields, we observe positive and negative drag around the double charge neutrality point, due to the competition of momentum and energy drag effects and also the probing geometry [1]. In the quantum Hall regime, both the longitudinal and transverse drag signal vanish at integer filling factors in either layer, despite the fact that at *T* = 50…100 K no QHE signatures are apparent in the direct transport. This is attributed to incompressible states appearing at integer filling factors, suppressing the drag response, similar to results reported for single layer graphene [2]. Those effects are well described in the Oppen-Simon-Stern theory [3], using the transport characterization of both layers. In addition, further regular patterns of vanishing drag appear in the QHE regime that we tentatively ascribe to different responses in the overlapping and non-overlapping parts of the sample. Finally, at *T* = 1.4 K, we observe indications of a condensate phase of magneto-excitons [4,5], appearing at a constant sum of the individual filling factors $\nu_{tot} = \nu_{bot} + \nu_{top} = \pm1, \pm3, \pm5$.

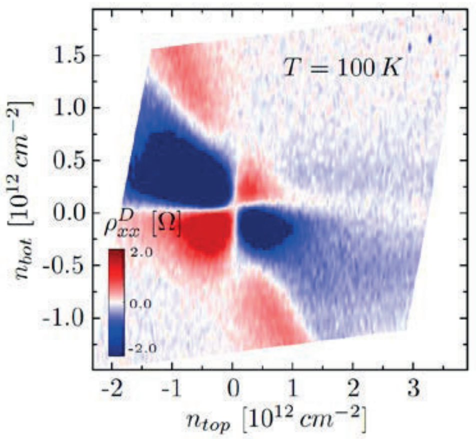


**Fig. 1:** Drag resistance at zero field and *T* = 100 K, showing both polarities depending on the polarities of the individual layers.

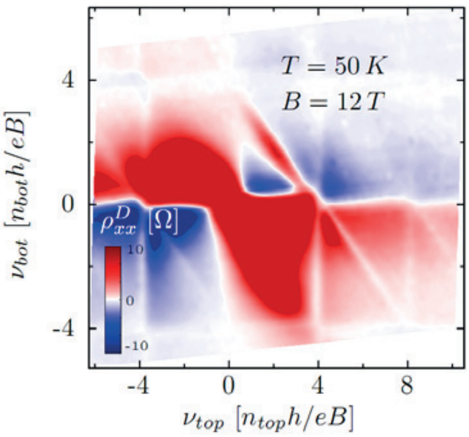


**Fig. 2:** Longitudinal drag resistance in the quantum Hall regime showing features at integer filling factors in the individual layers, but also additional diagonal lines.

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# A cascade of phase transitions in an orbitally mixed half-filled Landau level

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Landau levels (LL) in high quality two-dimensional electron systems (2DES) host an array of fractionalized electronic phases whose nature depends on their polarization in competing orbital and spin degrees of freedom. The LL index ($N$) plays an important role in determining the ground state of a half filled level, with the emergent Fermi-sea that forms in $N = 0$ displaying instabilities towards pairing in $N = 1$. Here we present physics of high mobility ZnO-based 2DES [1,2] at filling factor ν = 5/2 as the orbital quantum number of electrons is continuously tuned between $N = 1$ and 0 character [3]. We perform this by rotating a sample within the magnetic field to selectively enhance the total field ($B_t$) which acts to enhance the Zeeman coupling of carriers.

In contrast to the naive expectation of a first-order transition between level-polarized states, a rich cascade of five phases with distinct transport features are resolved as charge is gradually transferred between the two levels. In addition to incompressible (in $N = 1$, Fig. 1**a**) and compressible states (in $N = 0$, Fig. 1**e**), intermediate polarizations witness additional compressible (**b**), incompressible (**c**) and anisotropic nematic phases (**d**). The emergence of these unexpected phases in an orbitally mixed regime when the levels are near degeneracy motivates speculation this is a promising system for realizing unanticipated flavors of inter-level coherent states at fractional filling factors.

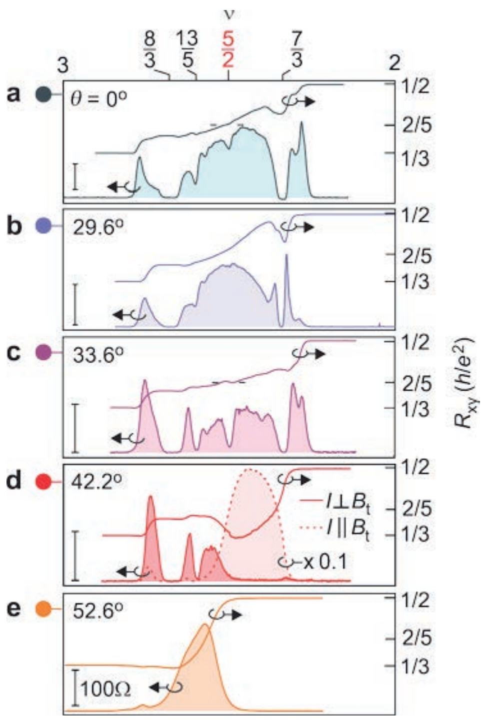


**Fig 1:** Magnetotransport traces of at defined tilt angles (θ) showing representative phases of the partial filling factor (ν).

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Poster 8

# Quantum Hall Effect: Where does the current flow for the quantized Hall resistance?

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In our group, detailed scanning probe measurements have been performed on various quantum Hall samples over the last two decades [1–5], revealing the actual Hall potential profiles and current distributions over the width of such samples under different conditions. Even the Hall potential profiles towards electrically induced breakdown of the quantum Hall effect have been measured and understood [6].

It was found that the current distribution within a quantum Hall plateau varies systematically with increasing magnetic field. Within a quantum Hall plateau, one can identify an edge- and a bulk-dominated quantum Hall regime. The results contradict to the edge-state picture commonly used.

Based on these investigations, supported by theoretical work of Rolf Gerhardts and coworkers, we can clearly state that in case of a quantized Hall resistance the externally **biased current is carried dissipationless in extended, electronically incompressible regions of the sample**, i.e., by electronic states under the local Fermi level, driven by the Hall voltage drop over these incompressible regions [7,8]. This is actually the key to understand the robustness of the quantum Hall effect.

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# Tuning the Quantum Hall Plateau Widths by Gate Electrodes

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From scanning probe experiments we know that the Hall voltage drop in quantum Hall samples is governed by the electrically incompressible landscape within the two-dimensional electron system self-consistently changing with magnetic field and applied voltage [1,2].

Due to the inhomogeneity of the electron density within a cross section of the sample – depletion towards the edges, long-range variations in the bulk – the incompressible landscape varies with changing the magnetic field. Indeed we could demonstrate by our Hall potential profile measurements that at the lower magnetic field side of the quantum Hall plateau the biased current flows in the innermost incompressible strip running inside the depletion region along the edges ('edge-dominated quantum Hall regime') whereas at the upper magnetic field side of the quantum Hall plateau, the current flows through the incompressible bulk ('bulk-dominated regime').

Here we present electrically induced breakdown measurements on quantum Hall samples with widths varying from few µm to several tens of µm which allow us to identify the edge- and bulk-dominated quantum Hall regime. Measuring the longitudinal voltage drop as a function of magnetic field and applied voltage, the asymmetry between low and high magnetic field side of the quantum Hall plateau becomes striking – very consistent with our microscope picture of the integer quantum Hall effect.

By enhancing the partial depletion in front of ohmic contacts probing the electrical potentials at the sample edges we can extend the lower magnetic field side of the zero resistance state from filling factor

$\nu = 2$ down to $\nu = 4$. At the same time the quantum Hall plateau is only partially extended to lower magnetic fields, i.e. $R_{xx} = 0$ does not necessarily mean $R_{xy}$ being quantized. Here presence or absence of incompressiblity in front of source and drain contacts plays the key role.
By using gates on top of the edges of our samples we can tune the electron density profile from the depletion to the accumulation regime. The latter case means in the edge state picture counter-propagating edge states. The measurements show an extension of the quantum Hall plateau on the higher magnetic field side, consistent with our expectation.

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Poster 10

# A scanning single-electron transistor array microscope probes the Hall potential profile in the ν = 2/3 fractional quantum Hall state at 40 mK

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The Hall potential profile and thus the current distribution in integer quantum Hall regime have been measured on various samples since 1999 [1] by an electrostatic potential probing scanning force microscope, limited to temperatures above 1.4 K. The results contradict the widely used edge-state picture and have given a new microscopic picture for the integer QHE [2]. Similar measurements in the fractional quantum Hall regime require much lower temperature and a strongly enhanced sensitivity.

Thus we have built a scanning probe microscope using a 1D array of eight single-electron transistors (SET), each acting as an independently operated local electrometer [3]. The instrument is working at about 40 mK electron temperature and up to applied magnetic fields of 18 T.

We present Hall potential profile measurements in the integer quantum Hall regime. The results confirm our previous results [1] obtained at 1.4 K. Further we present the evolution of the Hall potential profile and therefore the current distribution with rising magnetic field passing the fractional quantum Hall plateau assigned to the Landau level filling factor ν = 2/3.

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# Model calculations of current distribution in narrow Hall bars under the conditions of the integer quantum Hall effect and its breakdown

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Scanning force microscopy reveals an interesting spatial distribution of a current applied to a narrow Hall bar under the conditions of the integer quantum Hall effect and its breakdown. Apparently the current flows nearly dissipationless through "incompressible stripes", with positions and widths, which depend strongly on the applied magnetic field, but also on the strength of the applied current [1,2]. We present recent results of a self-consistent screening and transport theory, which nicely explains most of these observed phenomena as resulting from non-linear feed-back effects of the applied current on the electron distribution [1], from Joule heating [3], and from peculiar inhomogeneities of the electron distribution. Emphasis is put on the current-induced asymmetry of the current distribution in the edge-dominated regime of low magnetic fields within a quantum-Hall-plateau, and of the sample inhomogeneity in the bulk-dominated regime observed at higher magnetic fields in the same plateau.

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# Probing strong correlations in graphene at the Van Hove singularity

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Far away from the Diract point, the band structure of monolayer graphene features a Van Hove singularity (VHS): a point with theoretically infinite density of states. The Dirac cones are warped and touch at the M points, eventually creating one large hole pocket. In this regime, the effective mass diverges and the electron-electron interaction strength becomes very large. Many competing instabilities have been predicted at the VHS [1]: spin- or charge density waves, metal-insulator transitions and unconventional superconductivity. Realizing this state, however, is a formidable challenge.

Using a novel intercalation technique, we demonstrate that graphene on the (0001) surface of silicon carbide can be doped to the required carrier density. Earlier attempts [2] have observed a highly renormalized Fermi surface, but further investigations were hindered by the chemical instability of the dopants. By careful choice of intercalant, we have managed to stabilize the graphene to the extent that it can be transferred outside of the growth chamber and into a He-3 dilution unit.

In this study, both photoemission and magnetotransport are used to probe the correlations at the VHS. The impact of the Lifshitz transition at the VHS and potential phases at low temperature are identified and compared with theoretical predictions. The observations will be related to phenomena in twisted bilayer graphene and other layered compounds.

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# New 5-point Van der Pauw Method for Characterizing Anisotropic Conductors: Studies of Exfoliated Black Phosphorus

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A 5-point measurement method is introduced, whereby the full anisotropic conductivity tensor of an arbitrarily shaped sample can be determined [1]. This technique is used to characterize exfoliated black phosphorous, determining the temperature and gate-voltage dependence of the in-plane anisotropy. In addition, we examine the disorder-related transient conductivity, and observe that the commonly observed hysteresis in both electrical and photoluminescence studies of 2D materials can be characterized as a heavy-tail transient response to a step-function excitation. Dispersive diffusion equations successfully fit the transients in both the pristine and highly disordered sample limits, and a microscopic model for the response is provided, based on the continuous-time random walk model. Finally, we observe for the first time a generalized scaling behavior for the gated conductivity of 2D materials with disorder strength.

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Poster 14

# Determination of $Al_{0.2}Ga_{0.8}Sb$/GaSb transport properties

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GaSb/AlGaSb, the unknown relative of the famous GaAs/AlGaAs system, has been significantly under-researched in the field of electronic devices, despite promising properties of low effective mass and high dielectric constant which would allow the creation of high mobility devices [1]. GaSb investigations have been extensive in the field of optoelectronics, but limited to only basic bulk studies in the field of magnetotransport [2,3]. More advanced structures, such as two-dimensional electron gases (2DEGs) formed from heterojunction and quantum well structures are being realised in this work, through simulation, growth and measurement. The objective is to study magnetotransport properties of GaSb/AlGaSb 2DEGs for the first time using a magnetic field range up to 15 T, a Hall bar geometry following the work of Foxon and Harris is being used, with varying aspect ratios. Simulated and experimental temperature dependant transport properties will be presented for various GaSb/AlGaSb structures, putting confined GaSb on the electrical map.

Initially, a growth trial was carried out investigating the unintentional p-type doping in GaSb, which originates from a gallium antisite (GaSb). Finding a growth condition with reduced defects is the greatest chance for better quality, high mobility samples (Fig. 1 left). It was found that the unintentional doping is dependent on both the growth temperature and the V/III ratio. It was found that a V/III ratio of 1.3 and a substrate temperature of 475°C provided the lowest p-type carrier density and highest momentum relaxation time. The activation of the inherent *p*-type defects suggests that their contribution to the carrier density becomes insignificant at below 50 K. With the addition of *n*-type dopant this could lead to interesting quantum structures where band structure is vastly different across a temperature range.

With new knowledge of the material properties, revised simulations were performed with the aim of improving transport properties in a GaSb/$Al_{0.2}Ga_{0.8}Sb$ 2DEGs. Theoretical band structures and transport results were simulated using Nextnano software [4]. The most promising of which are being physically realised.

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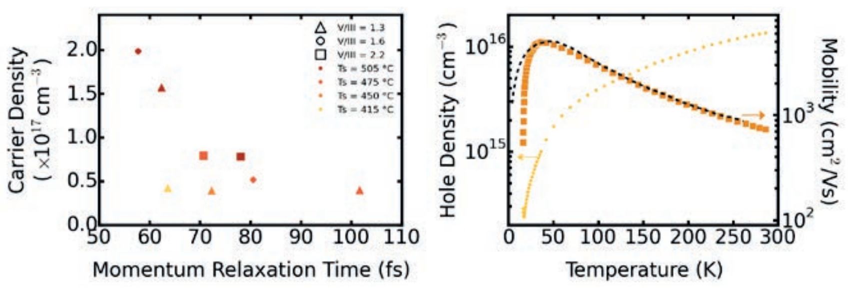


**Fig. 1. Left:** Carrier density against momentum relaxation time at room temperature for undoped GaSb showing different growth conditions to outline the native defects occurring in GaSb. The legend shows the substrate temperature and the V/III ratio for each condition. **Right:** Hole mobility and density against temperature for an undoped GaSb sample with a comparison to Dutta *et al.* (dashed line) [3].

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# Quasiparticle Tunneling in the Lowest Landau Level

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In this work, we set out to verify quantitatively whether quasiparticle tunneling theory [1] appropriately describes tunneling between edge channels in the lowest Landau level.

Tunneling conductance is a potentially powerful probe of the nature of FQH states. However, to date it has not been verified that the theoretically expected scaling parameters are obtained for states of which the wave function and the effective charge is known with a high degree of confidence, such as the Laughlin state at $\nu = 1/3$. Interpretation of the scaling parameters measured in the second Landau level, in particular at $\nu = 5/2$ [2–5], thus lack a solid experimental basis.

We present measurements of quasiparticle tunneling across a constriction at $\nu = 1/3$ and $\nu = 1 + 1/3$. We find that data in the weak backscattering regime is in qualitative contrast to theoretical predictions. On the other hand, the theory developed for weak backscattering describes well experimental data acquired in the strong backscattering regime, and the analysis leads to an effective charge of $e/3$ in the $\nu = 1/3$ state. The interaction parameter $g$ is however not universal and depends strongly on the gate voltage applied to the constriction. At $\nu = 4/3$, a more complex picture emerges. We propose an interpretation in terms of selective tunneling between the multiple modes present at the edge.

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# The generalized pseudopotential descriptions for FQHE without rotational symmetry

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Haldane pseudopotentials have played a key role in the study of the fractional quantum Hall (FQH) effect as they allow an arbitrary rotationally-invariant interaction to be expanded over projectors onto the two-particle eigenstates of relative angular momentum. Here we introduce a more general class of pseudopotentials that form a complete basis in the cases where rotational symmetry is explicitly broken, e.g., due to tilted magnetic field or tilted dipolar fermions. Similar to the standard isotropic pseudopotentials, the generalized pseudopotentials are also parametrized by a unimodular metric, which groups the effective interactions into equivalence classes, and is particularly useful in determining optimal model Hamiltonians of the anisotropic FQH fluids.

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# Principal component analysis of quantum Hall wave functions

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The fractional quantum Hall effect demonstrates the robustness of topological properties in many-body systems. The effect of mass and interaction anisotropy can be understood in terms of a geometrical description. We present a study of the evolution of quantum Hall wave functions with interaction anisotropy by a statistical learning technique known as the principal component analysis (PCA). We show that the topological and geometrical aspects of a family of wave functions can be readily separated by the PCA. We discuss how to use the PCA to extract wave function metric and to determine the stability of a fractional quantum Hall phase.

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Poster 18

# Comparing magnetorotons at fillings 1/3 and 7/3

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Quantum liquids have collective modes that rule their low-energy behaviour. In the case of liquid He-4 there is a branch of collective excitations above the ground state that is phonon-like at long wavelength and crosses over to the so-called roton minimum at some nontrivial value of the momentum. Two-dimensional electrons gases in the fractional quantum Hall regime also exhibit remarkable collective modes. In the incompressible liquid state of electrons at filling factor 1/3 of the lowest Landau level it is known that the density excitations are gapped at all wavevectors but have also a roton-like minimum, the magnetoroton of Girvin, MacDonald and Platzman. This very special state of matter is famous for also having quasiparticle excitations with fractional charge and statistics related to its topological order. Since these topological properties have a universal character one may wonder if collective excitations have also some universal character.

By studying the quantum Hall state at filling factor 7/3 which is the first Landau level counterpart of the Laughlin state at filling 1/3 I show that the magnetoroton mode while gapped has a strikingly different shape with now two minima and only one is described by the single-mode approximation. This is an effect that is revealed most clearly when taking into account the finite width in the perpendicular direction of the two-dimensional electron gas. These results are based on exact diagonalizations of small systems and are stable with respect to Landau level mixing at least in perturbation theory. Prospects of experimental observations are discussed, both in semiconducting devices and in graphene devices with Moiré pattern.

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# Single atom Quantum Hall Effect with the Trojan Wave Packets

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Almost 25 years ago we have discovered that the circularly Polarized Electromagnetic Field is capable to maintain the stable, non-dispersing and totally shape-invariant soliton-like electron wave packets moving around the hydrogen atom nucleus on circular orbits parallel to the plane of the electromagnetic field polarization. Because of the similarity of the stabilization and the confinement mechanism in the harmonic small oscillation limit to the Trojan Asteroids stably following the Jupiter orbital motion around the Sun at Lagrange equilibrium points L4 and L5 we called those states Trojan Wave Packets [1]. We had further developed the nonlinear pendulum theory with the use of the Mathieu functions predicting that the expectation values of the observables in the Trojan state experience the Bloch oscillations as functions of the field frequency [2].

Here we point out that that Trojan Wave Packet allows the observation of the effect analogical to the Quantum Hall Effect [3] while smoothly changing (chirping) the frequency of the Circularly Polarized Field instead of the magnetic field. The single electron motion around the circle may be interpreted as the Hall current while the voltage between the hydrogen nucleus and the electron orbital point as the induced Hall voltage because it is perpendicular to this current. Defining the single electron Hall current as:

$$I = e / T = \omega e / 2\pi$$

and the Hall voltage between the orbit and the nucleus

$$U = \varepsilon r_0$$

We find at the points of the exact resonance

$$r_{0n} = n^2 a_0$$
$$\omega_n = 2R_\infty / n^3\hbar$$

quantization of the basic resistance as

$$R_n = U_n / I_n = \varepsilon_{sc}(h/e^2)n^5 = \varepsilon_{sc} n^5 25812.807557\Omega$$

where

$$r_0 = < r >$$

is the Trojan Wave Packet orbit radius average which is subjected to Bloch oscillations with ω and we define the dimensionless electric field scaled to the field at the first Bohr orbit i.e.

$$\varepsilon = (e / 4\pi\varepsilon_0 a_0^2)\varepsilon_{sc}$$

Unlike for the normal Quantum Hall Effect the quantized resistance is proportional to the Hall resistance with the scaled field and its quantization is quintic in the quantum number n and not the inverse of in the integer.

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Poster 20

# Quantum Hall Ferromagnetism in Two-Dimensional Atomic Lattices

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Since the seminal discovery of graphene, two-dimensional (2D) atomic crystals have proven to be an exciting playground for investigating novel quantum Hall (QH) phenomena. The most discussed representatives in the field have been the prime examples mono- and bilayer graphene [1,2]. But this class of systems also includes other novel materials such as the 2D surface states of crystals (for example the (111) surface of elemental bismuth [3]), mono- and few-layer transition metal dichalcogenides [4], or heterostructures such as graphene on hexagonal boron nitride [5]. We theoretically investigate these novel systems in the QH regime focussing on the multiple discrete degrees of freedom the electrons may carry, such as, e.g., spin and valley quantum numbers, or a Landau Level index. Within the framework of QH ferromagnetism, i.e., treating the electronic degrees of freedom as spins and isospins, different aspects of the systems are explored by analysing the resulting spin and isospin structure. Hartree Fock theory is employed to study the influence of electronic interactions in these multi-component spin and isospin system on the mean field level [6].

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# Using fractional quantum Hall states to enhance polariton-polariton interactions

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We investigate a two-dimensional electron system (2DES) embedded in an optical cavity. Cavity photons are strongly coupled to Fermi polarons, which leads to the formation of polaron polaritons [1,2]. The light-matter coupling strength is sensitive to the electronic ground state. In particular when applying an external magnetic field it is modified when the electrons form integer and fractional quantum Hall states [1,3]. Comparing left- and right-circularly polarized polariton resonances, we observe changes in light-matter coupling strength related to spin polarization of the 2DES. At integer filling, polariton formation is suppressed in the already fully occupied Landau level. At fractional filling, spin polarization leads to a more subtle effect. As the polaron is formed by electrons with spin opposite to the electron forming the exciton, spin polarization of the 2DES can prevent polaron formation. The optical signature is again a reduction of the light-matter coupling strength for the suppressed transition.

In this work, we observe nonlinear energy shifts in the lower and upper polariton lines at certain 2DES filling factors and explore their time-resolved nonlinear optical response. The polariton-polariton interactions are increased at fractional quantum Hall states, more than an order of magnitude in the case of filling factor 2/5. We speculate that this measurement goes beyond signatures of spin polarization of the 2DES and is sensitive to other ground state properties.

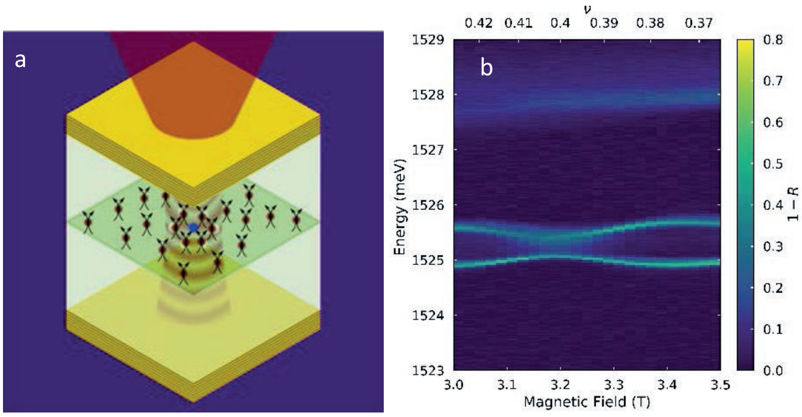


**Fig.1:** (a) We embed a 2DES in a semiconductor microcavity. (b) We observe two polariton resonances split by more than their linewidths, demonstrating the strong coupling regime between light and matter excitations (only $\sigma^-$ polarization is shown). Tracing the distance between the lower and upper polariton resonances around filling factor 2/5, we see a reduction in coupling strength. This feature around filling 2/5 corresponds to one of the 2DES states where we measured an enhanced optical nonlinearity.

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Poster 22

# Charge equilibration in integer and fractional quantum Hall edge channels in an anti-Hall bar device

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The concept of edge channels formed along the boundary of a two dimensional electron gas has been accepted as a basic intergradient for understanding the quantum Hall (QH) effect [1]. When two edge channels are running parallel to each other in close proximity, charge equilibration associated with charge transfer between the channels alters the conductance of the system. While this has been studied for a few decades in the integer QH regime, charge equilibration in the fractional QH regime is not systematically revealed. Here, we investigate such charge equilibration in an anti-Hall bar device. This allows us to perform multi-terminal measurements on a particular inner edge channel, and should be useful for identifying the absence of backscattering.

Our anti-Hall bar device is schematically shown in Fig. 1(a), where 6 quasi-Corbino type ohmic contacts, $\Omega_1 - \Omega_6$, and a Hall-bar shaped metal gate with width *d* are placed. By tuning the magnetic field *B* and the gate voltage $V_g$, the gated region with filling factor $\nu_g$ and the ungated region with $\nu_b$ can be prepared in either integer or fractional QH states. For instance with integer $\nu_g$ greater than integer $\nu_b$ in Fig. 1(b), the inner edge channel(s) forms a closed loop, which is coupled to the outer edge channels with charge equilibration for the length *d*. Similar channel geometries appear for fractional state $\nu_g = 4/3$ inside integer state $\nu_b = 1$ and for fractional state $\nu_g = 2/3$ inside integer state $\nu_b = 1$. In these cases, the conductance between $\Omega_1$ and $\Omega_4$ is sensitive to the charge equilibration, while $V_{xx}$ and $V_{xy}$ can be used to confirm the absence of backscattering in both ungated and gated regions. In this way, charge equilibration can be investigated systematically for various QH states.

In this work, we used anti-Hall bars of width $d = 10$, 50, and 100 μm on a standard AlGaAs/GaAs heterostructure ($n = 1.7\times10^{11}$ cm$^{-2}$ and $\mu = 4.6\times10^{6}$ cm$^2$/Vs). A low-frequency (37 Hz) AC voltage of amplitude $V_{AC} = 30$ μV was applied to $\Omega_1$, and the conductance $G = I_{AC}/V_{AC}$ as well as the voltage $V_{xx}$ and $V_{xy}$ were measured. Figure 1(c) shows a color plot of $V_{xx}$ for $d = 100$ μm device, where signatures of integer and fractional QH state ($\nu_g$, $\nu_b$) are labelled. The regions showing too small $G < 0.1\, e^2/h$ to evaluate $V_{xx}$ were greyed out. Clean inner edge channels without showing backscattering are formed in the white regions ($V_{xx} << V_{AC}$). For instance, the vanishing $V_{xx}$ and finite $G$ and $V_{xy}$ (not shown) for $\nu_g = 2$ at $\nu_b = 1$ ensure dissipationless transport in the inner edge channels. The backscattering and the charge equilibration are studied by comparing the measured values with the generalized Landauer-Buttiker formula. The anti-Hall bar geometry would be helpful for understanding the edge structures as well as the edge reconstruction phenomena in hole-conjugate fractional QH states.

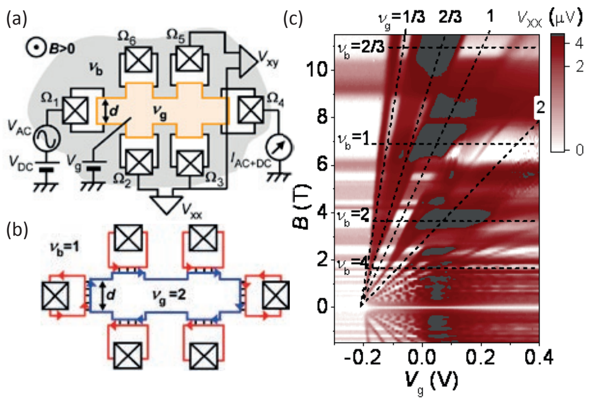


**Fig. 1**. (a) A Schematic of the anti-Hall bar device. (b) Charge equilibration expected for edge channels at $\nu_g = 2$ and $\nu_b = 1$. (c) Color plot of $V_{xx}$ as a function of *B* and $V_g$. The regions showing too small $G < 0.1\, e^2/h$ to evaluate $V_{xx}$ were greyed out.

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# 3D Quantum Hall effect in Topological Semimetals

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The quantum Hall effect is usually observed in 2D systems. We show that the Fermi arcs can give rise to a distinctive 3D quantum Hall effect in topological semimetals. Because of the topological constraint, the Fermi arc at a single surface has an open Fermi surface, which cannot host the quantum Hall effect. Via a "wormhole" tunneling assisted by the Weyl nodes, the Fermi arcs at opposite surfaces can form a complete Fermi loop and support the quantum Hall effect. The edge states of the Fermi arcs show a unique 3D distribution, giving an example of (d−2)-dimensional boundary states. This is distinctly different from the surface-state quantum Hall effect from a single surface of topological insulator. As the Fermi energy sweeps through the Weyl nodes, the sheet Hall conductivity evolves from the $1/B$ dependence to quantized plateaus at the Weyl nodes. This behavior can be realized by tuning gate voltages in a slab of topological semimetal, such as the TaAs family, $Cd_3As_2$, or $Na_3Bi$. This work will be instructive not only for searching transport signatures of the Fermi arcs but also for exploring novel electron gases in other topological phases of matter.

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Poster 24

# Tunable dispersion of the edge states in the integer quantum Hall effect

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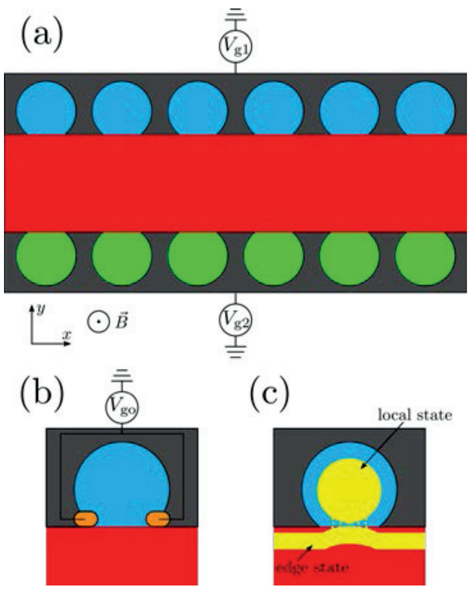
Topological aspects represent currently a boosting area in condensed matter physics [1,2]. Yet there are very few suggestions for technical applications of topological phenomena. Still, the most important is the calibration of resistance standards by means of the integer quantum Hall effect. We propose modifications of samples displaying the integer quantum Hall effect which render the tunability of the Fermi velocity possible by external control parameters such as gate voltages [3]. In this way, so far unexplored possibilities arise to realize devices such as tunable delay lines and interferometers.




Panel (a): proposal of a decorated quantum Hall sample with tunable Fermi velocity. A perpendicular magnetic field puts the two-dimensional electron gas in the quantum Hall phase. Two independent gate voltages $V_{g1}$ and $V_{g2}$ change the potential of the blue bays at the upper boundary and of the green bays at the lower boundary, respectively. The grey area is inaccessible to the electrons. The size of the opening of the bays to the bulk 2DEG can be controlled by a gate voltage $V_{go}$ as depicted in panel (b). The size of the opening controls the degree of hybridization of the local mode within the bays and the edge mode in the 2D bulk, see panel (c).

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# Advances in electron transport in InSb/$Al_xIn_{1-x}Sb$ quantum wells

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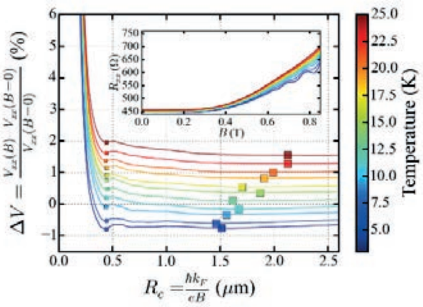
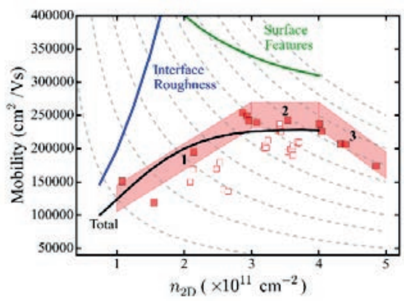
Narrow-gap indium antimonide (InSb) based heterostructures are of increasing interest for use in quantum transport devices. InSb exhibits the lowest electron effective mass ($m^* = 0.014\ m_e$) and highest reported room-temperature electron mobility ($\mu$ = 78,000 $cm^2$/Vs) of any compound semiconductor, as well as a strong spin-orbit interaction and large Landé $g$-factor ($g \approx 50$). These properties have gained attention for use in spintronics and quantum information control, as well as the possibility of the realisation of Majorana Fermions in a system where potentially advanced planar fabrication can be exploited.

We report on advances in electronic transport measurement and corresponding modelling of high mobility InSb/$Al_xIn_{1-x}Sb$ quantum well heterostructures, demonstrating the critical scattering mechanisms across a range of samples [1]. Through the use of Differential Interference Contrast DIC (Nomarski) optical imaging we have observed characteristic surface roughness [2], and we present evidence for the effects of these on magnetoresistance measurements. Using a Monte Carlo model combined with Drude transport modelling, and modified 2D Landauer-Büttiker tunnelling calculations [3], we show that transport in these structures can be successfully described using a potential barrier model for grain boundaries, where these effective Schottky like barriers are inferred to pin at ≈ 78% of the mid gap value. We further expand on this model using an analytic approximation to accurately predict the low temperature mobility behaviour. Using a modified transport model combined with this potential barrier scheme we can successfully describe measured mobilities across a wide range of samples and demonstrate that there is the potential for vast improvements in this material system given correct buffer redesign and significant defect reduction.

This work was supported by the UK Engineering and Physical Sciences Research Council.




a)




(b)

**Fig. 1:** a) Magnetoresistance measurements as a function of temperature showing local minima associated with proposed scattering mechanisms (surface feature related scattering and background impurity scattering). Inset) Corresponding longitudinal $R_{xx}$ resistance against $B$-field. b) Carrier density ($n_{2D}$) vs mobility for a series of samples with increased doping (filled squares), with 3 regions shown. Lines show transport model fit with limiting contributions labelled [2].

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Poster 26

# Hall electric field activated resistivity and the breakdown of the quantum Hall effect in GaAs and graphene

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A number of reports [1–3] have previously shown that the resistivity minima at the quantum Hall condition show electric field dependence of the activated conduction which are given by the equations: $\rho_{xx} = \rho_0 \exp(-E_A/kT)$ and $E_A = \Delta_0 - eaE_H$, where $a$ is thought to be associated with an activation length and $E_H$ is the Hall electric field. To date the explanation of this behavior is uncertain. Here we demonstrate that this behavior occurs in typical GaAs/GaAlAs heterojunctions as used for standard applications and explore the highly asymmetric conduction and breakdown behavior for different regions of the resistivity minimum.

We investigate the dependence of the conductivity on Hall field, temperature and magnetic field close to the $\nu = 2$ minimum in a variety of Hall bars of different widths. We show that the localization lengths exhibit highly asymmetric behavior for conduction dominated by the $N = 0$ or $N = 1$ Landau levels, with localization lengths much shorter when the chemical potential is closest to the $N = 0$ level and that this behavior is most pronounced in a narrow Hall bar. Beyond the Hall field activated region there is a sudden increase in resistivity at current densities attributable to the quantum Hall breakdown region. This behavior persists well beyond the resistivity minimum and the resistivity displays a well pronounced negative differential resistance even up to temperatures as high as 15 K. These results suggest that around the critical breakdown current regime there is a dramatic change in the conduction process under a variety of different parameters.

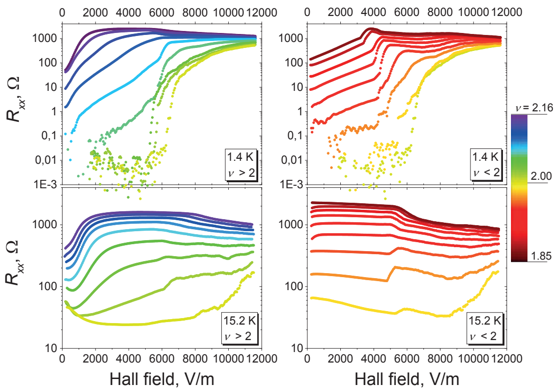


**Fig. 1:** Resisitivity of the $\nu = 2$ minimum as a function of the Hall electric field for a set of occupancies around the minimum value for a GaAs/GaAlAs heterojunction in the magnetic field range of 9.5–11.2 T.

We have also studied the same behavior in low density epitaxial graphene samples where the chemical potential lies close to the Dirac point, which are good candidates for new resistance standards [4]. The graphene shows similar activation behavior with a very similar activation length of order 300 nm, comparable to typical length scales determined from potential profiling.

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# Magneto-transport of 2DEGs ultrastongly coupled to vacuum fields – probed by weak THz irradiation

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The second quantization of quantum field theory requires electromagnetic field excitations described as a harmonic oscillator (Photons) to be quantized. Each modes zero-point energy $E = 1/2\hbar\omega$ is responsible for vacuum electric fields $E_{\text{vac}} = (\hbar\omega/\epsilon\epsilon_0 V_{cav})^{0.5}$ As such, they are responsible for the Casmir-Polder force, the Lamb shift and a non-zero spontaneous emission rate. In the recent decades, engineering of light-matter coupling giving rise to significant vacuum Rabi splittings between a matter and photon excitation became a very important field of research in Quantum optics. Vacuum electric fields, despite their zero expectation value, are predicted to be observable in magneto-transport with sufficiently large vacuum Rabi splittings [1,2].

Here, we present a GaAs/AlGaAs-based Hall bar inside a planar microwave cavity with a resonance at 140 GHz. The latter couples ultra-strongly to the electrons at the Fermi energy that contribute to transport [3]. We probe the changes in the longitudinal magneto-resistance $\Delta\rho_{xx}$ altered by mixed light-matter particles (polaritons) by weakly illuminating the sample with a widely tunable single frequency sub-THz source (60 GHz to 600 GHz) at temperatures of around 100 mK. On average, the source excites only a ~10 polaritons to the successive Landau level. The measurements reveal that, in contrast to the extended states, the localised states responsible for the features of the integer quantum Hall transport only weakly couple to the vacuum field of the cavity.

As an outlook, we are currently performing experiments to manipulate the vacuum electric field in situ, in order to demonstrate the effect of vacuum electric fields on Quantum Hall transport in complete absence of a probing photons.

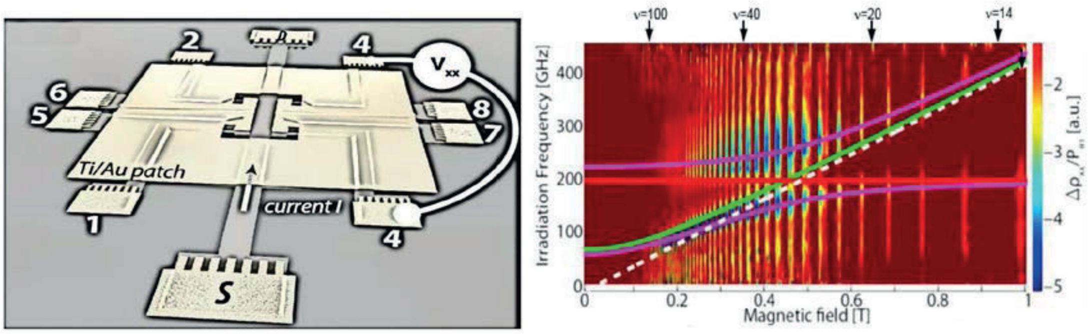


**Fig. 1:** (left) Schematic of Hallbar with 8 contacts all inside the region where the electron gas is ultrastrongly coupled to the cavity formed by a patterned sheet of Ti/Au lying around the Hallbar. (right) Longitudinal resistance photo response to Sub-THz illumination as function of frequency and magnetic field shows strong filling factor ν dependence and signatures of coupling to vacuum fields.

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Poster 28

# Patterned Back Gates suitable for Ultra-High Quality GaAs/AlGaAs Heterostructure Epitaxy

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Gate patterning is mandatory for meso- and nanoscopic scale devices such as quantum point contacts. While patterned top gates can be realized with relative ease, the implementation of patterned back gates is very demanding. Ideally, the patterned back gate needs to be buried between substrate and heterostructure to attain sufficiently low distance between back gate and two dimensional electron gas (2DEG). Moreover, the quality of the heterostructure epitaxy should not be limited by a patterned substrate. We developed a reliable technique to implement patterned back gates for ultra-high quality 2DEGs suitable for nanoscopic devices.

We found a way [1] to overcome the limitation of prior approaches and define back gate patterns directly on the epitaxial surface of the GaAs substrate using oxygen implantation on silicon doped GaAs substrates to electrically insulate regions (passively written gates). Recently, we realized actively written gates by implanting silicon directly on GaAs substrates and subsequent annealing for dopants activation.

The sample fabrication (see Fig. 1) is efficient, reliable and scalable. It starts with standard photo-lithography on a GaAs wafer using photoresist as a selective absorber for the silicon ion implantation, followed by an "epiready" cleaning process as well as dopants activation in a MOCVD system (optional step depending on the growth temperature in the MBE). The samples are then overgrown with the desired heterostructure. Subsequently, mesa-structures with inherently separated contacts for 2DEG and back gate can be defined. The implantation parameters were optimized to achieve reliable gating as well as a minimal impact of the implantation on the surface quality of the substrate.

We use the back gating technique in order to probe individually contacted and gated bilayer systems. This opens the field of exotic phase diagrams of two 2DEGs as well as the forming of exciton condensate using an electron hole bilayer systems, which is able to access a Bose Einstein condensate (BEC) at higher temperatures compared to BECs achieved with atomic gases.

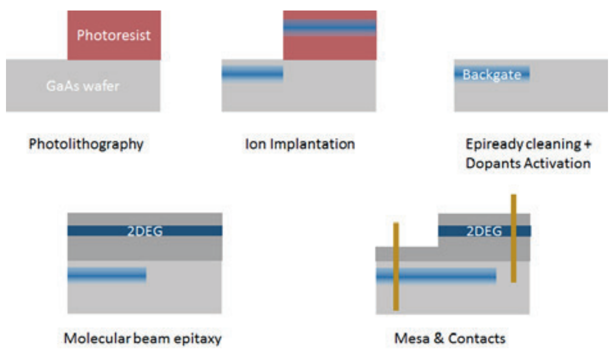


**Fig.1:** The five steps to fabricate heterostructures with patterned back gates. Details are given in the text.

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# Edge state spectroscopy in GaAs quantum wires

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We probe the integer quantum Hall edge states in a GaAs/AlGaAs 2D electron gas at low electron temperature $T_e \approx$ 10mK using an adjacent, tunnel coupled quantum wire. The tunneling current peaks when energy and momentum conservation are fulfilled. A vector magnetic field provides a momentum kick to the tunneling electrons and allows for spectroscopic imaging of more than the first ten Landau level edge states [1] with nanometer real space resolution and down to magnetic fields around 10 mT where $\nu_{bulk} \approx 500$. Upon increasing the field, these states are compressed towards the sample edge, until eventually they become magnetically depopulated and move back into the bulk. In addition the spectroscopy experiment reveals spin splitting, fermi-level pinning, demonstrates the chiral nature of the current carrying edge states, and allows us to extract the exchange interaction in the quantum Hall regime. Theoretical predictions using both, an analytical model and numerical solutions from a single particle Schrödinger solver for hard wall confined Landau levels show excellent agreement with the experiment over the entire range of magnetic field.

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Poster 30

# Time-resolved tunneling between Landau levels in a weakly coupled quantum dot in the integer quantum Hall regime

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We study the electronic transport properties of weakly coupled quantum dots (QDs) in the integer and fractional quantum Hall regime in order to gain insights into the structure of edge channels and develop methods for the detection and manipulation of quasiparticle excitations. The nanostructures are formed by electrostatic gating of a high mobility 2DEG hosted in a GaAs/AlGaAs-heterostructure. In addition to conventional measurements of the current flowing through the nanostructures, we employ charge detection and real-time charge counting techniques [1].

We measure the transport current through a 1µm large QD (shown in Fig. 1(a)) in the QH regime between filling factor $2 > \nu > 1$ where the lowest two Landau levels form two compressible regions separated by an incompressible region. We observe modified Coulomb resonances when an electron is rearranged between the Landau levels in the QD (Fig. 1(b)). We measure tunneling of electrons between the two Landau levels with time resolution (Fig. 1(d)). Time-resolved tunneling between two Landau levels has previously been observed in early studies of large QDs in the integer quantum Hall regime [2]. Experiments have further demonstrated non-cyclic depopulation of Landau levels in a QD [3].

The excitations of the fractional quantum Hall states are predicted to behave as anyonic quasiparticles exhibiting fractional elementary charge [4]. The presented investigations open the way for time-resolved measurements of quasiparticle tunneling between Landau-levels in the fractional quantum Hall regime for investigating the properties of quasiparticles and in particular their electric charge.

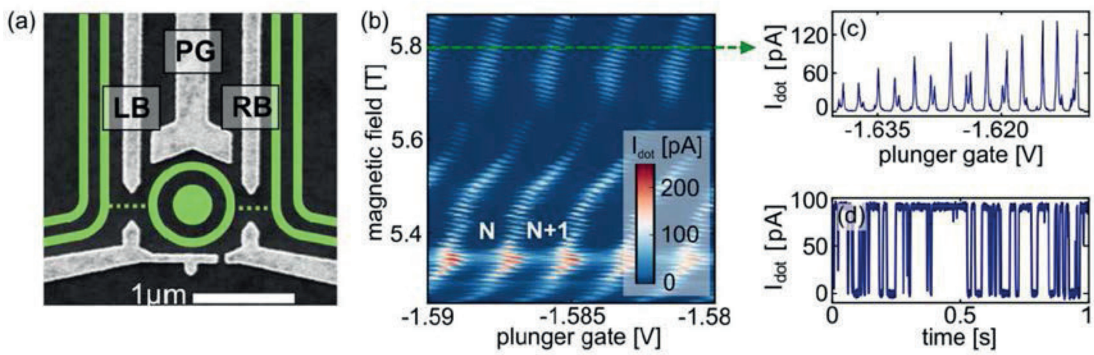


**Fig. 1:** (a) SEM image of sample with compressible regions schematically indicated in green, (b) current measured through the QD as function of magnetic field and plunger gate(PG) voltage, (c) split Coulomb peaks are observed as a function of plunger gate(PG) voltage, (d) timetrace of the QD current at fixed gate voltage and magnetic field shows switching whenever an electron tunnels between the Landau levels.

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# Hot-carriers induced breakdown of the Quantum Hall State in a single-layer graphene

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The robustness of the Integer Quantum Hall Effect (IQHE) in graphene grown on SiC enables the implementation of resistance metrology at relatively high temperatures and low magnetic fields. For high accuracy measurements of the Hall resistance, the bias current across the sample should be as high as possible, but not to exceed a critical value at which the Quantum Hall State breaks down. The break-down mechanisms in the QHE are studying for decades, but the knowledges gained on, for example on GaAs-based 2D structures, are not always transferable to new materials due to their different nature.

The energy dissipation occurs at the point where current is injected in the 2D electron or hole gas. Non-equilibrium hot electrons and heat are propagating along the channels in one direction due to the chiral nature of the charge and heat transport in the Quantum Hall Regime [3]. The hot electrons cooling mechanism due to acoustic phonons emission was recently analyzed theoretically [2] for a graphene in QHS. In this paper we present results of the critical current distribution along the conductive channel of a single-layer graphene structure in the IQHE regime. The information about the sample could be found in [1]. In order to avoid any corner effects, the sample was round-shaped.

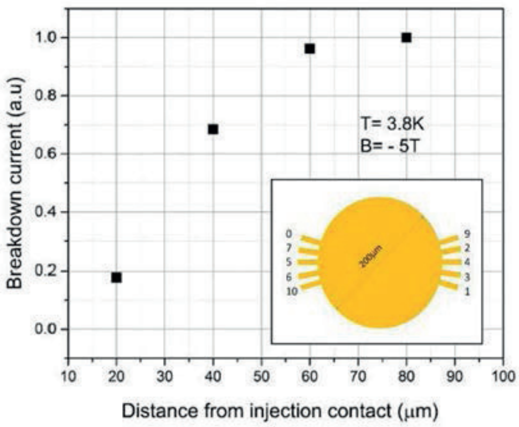


**Fig. 1:** Current-voltage characteristics for the filling factor ν = 2. Magnetic field orientation is from the sheet to the viewer. Voltage drops $V_{n\text{-}m}$ were measured along the edge conductive channel between contacts 0–7, 7–5, 5–6, 6–10. The bias currents $i_{S\text{–}D}$ was applied between contacts 2–10. Insert shows the sample topology. The distance between centers of contacts was measured from contact 10. Inset shows the sample layout. Carrier concentration was $n = 1.1{\cdot}10^{15}$ m$^{-2}$

From our experimental data we conclude that the hot electrons injected in graphene from the metal contacts cool down along the conductive channels to the base temperature on the distance of about 100 μm from the hotspot.

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# Advances in the development of the quantum Hall resistance standard in graphene grown by CVD on SiC for operation in relaxed experimental conditions

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In order to develop a reliable and practical electrical resistance standard, metrologists aim at exploiting the robustness of the quantum Hall effect (QHE) in graphene, coming from the very large energy gap between the two first Landau levels. At LNE, recent progress has been made by using graphene grown by the original technique of hydrogen/propane CVD on SiC and outstanding results have been obtained: the Hall resistance quantization has been observed with an excellent accuracy (to within relative uncertainty below $1{\cdot}10^{-9}$), in convenient experimental conditions (magnetic field down to 3.5 T, temperature up to 10 K or current up to 0.5 mA), much simpler and extended as compared to those required by GaAs/AlGaAs heterostructures. In addition, high-precision comparisons of the quantized Hall resistance in the graphene-based device and in a GaAs/AlGaAs-based device have led to a new demonstration of the QHE universality with the record relative uncertainty of $8.2{\cdot}10^{-11}$, which supports the exactness of the relation of the quantized Hall resistance to the Planck constant *h* and the elementary charge *e* only [1].

This poster describes supplementary quantum transport experiments performed up to 19 T and down to 0.3 K in a significant number of graphene-based quantum Hall devices obtained from graphene grown by CVD on SiC, similar to the one used for the above-mentioned demonstrations. The objectives were to investigate the technology reliability, *e.g.* the sample-to-sample reproducibility, stability and control of the electronic properties and device performance, as well as the structural key control parameters, and the underpinning physics.

For example, control of the charge carrier concentration has been attempted using corona discharge method with the objective to reduce the concentration and the operation magnetic field of the quantum Hall resistance standard down to a few teslas. As an other example, magnetotransport measurements as a function of temperature and current have been carried out to identify the dissipation mechanism limiting the Hall quantization: the existing variable range hopping models are questioned [2]. Most of our observations suggest that the buffer layer lying at the interface between the SiC substrate and graphene could impact both physics and performance of the devices.

Improving the reliability of graphene-based quantum Hall devices is necessary to realize the high promises of these devices for easier, cheaper, integrable and marketable quantum electrical measurement standards and sensors. For example, graphene is expected to render possible the development of a compact quantum multimeter combining the quantum Hall resistance standard and the Josephson voltage standard to deliver highly reproducible and universal electrical references for resistance, voltage, even current [3] and impedance measurements. The graphene-based quantum Hall resistance standard and, even more so, such a multimeter would dramatically help the dissemination, with the highest accuracy, of the coming soon revised International System of Units (SI) to be based on fundamental physical constants, like *h* and *e*.

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Poster 33

# The locality of incompressible stripes in the quantum Hall effect

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Since the experimental realisation of the integer quantised Hall effect in a two dimensional electron system subject to strong perpendicular magnetic fields in 1980, a central question has been the interrelation between the conductance quantisation and the topological properties of the system. It is conjectured that if the electron system is described by a Bloch hamiltonian, then the system is insulating in the bulk of the sample throughout the quantised Hall plateau due to magnetic field induced energy gap. Meanwhile, the system is conducting at the edges resembling a 2+1 dimensional topological insulator without the time-reversal symmetry. However, the validity of this conjecture remains unclear for finite size, non-periodically bounded real Hall bar devices. Here we show theoretically and experimentally that the close relationship proposed between the quantised Hall effect and the topological bulk insulator is prone to break for specific magnetic field intervals within the plateau evidenced by our magneto-transport measurements performed on GaAs/AlGaAs high purity Hall bars with two inner contacts embedded to bulk [1, 2]. On one hand, our experimental data presents a similar behaviour also for fractional states, in particular for 2/3, 3/5 and 4/3. On the other hand, the numerical findings show a similar behaviour at confined systems considering 5/2 state [3].

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Poster 34

# Negative Excess Shot Noise by Anyon Braiding

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Fractional charge and fractional statistics are the basic features of anyons. The fractional charges $e^*$ have been detected by shot noise at a quantum point contact (QPC) between two fractional quantum Hall edges. We predict the noise of electrical tunneling current $I$ at the QPC of the fractional-charge detection setup, when anyons are dilutely injected, from an additional edge biased by a voltage, to the setup in equilibrium. At large voltages, the nonequilibrium noise is *reduced* below the thermal equilibrium noise by the value $2e^*I$. This negative excess noise is opposite to usual positive Poisson noises such as the Poisson noise $2e^*I$ in the conventional fractional-charge detection. This is a signature of the Abelian fractional statistics, resulting from a process [1,2] where an anyon thermally excited at the QPC effectively braids around another anyon injected from the additional edge.

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Poster 35

# Quantum Hall effect as probe of the graphene layer quality

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In this report experimental results of the magneto-transport measurements over a wide interval of temperatures for two samples of graphene (#3084 and #3491) grown by chemical vapor deposition (CVD) on the SiC substrate [1] are presented. The formation of graphitized structure was confirmed by Micro-Raman spectroscopy. Hall bar samples with current channel of 540 µm long and 20 µm wide was patterned by photolithography on the graphene chip. Three pairs of the voltage probes were located evenly along the current channel allowing measurements of longitudinal and transvers voltages with respect to the current direction. That one's enable us to determine the longitudinal $R_{xx}$ as well as the $R_{xy}$ Hall resistance. Magneto-transport measurements were performed by Crio-Magnet installation [2] in Centre for Microelectronic and Nanotechnology (University of Rzeszow) enabling researches from 0.3 K to 300 K. The results obtained for sample #3084 are shown in Fig. 1. The well-defined quantized plateau in $R_{xy}$, accompanied by minima of $R_{xx}$ are observed at 0.4 K what explicitly indicate on the Integer Quantum Hall Effect (IQHE) and Shubnikov-de Haas (SdH) oscillations characteristic for 2D electron gas. The consequence of plateau and the residual values in plateau correspond to the regularity $R_{xy} = e^2/vh$ with filling factor $v = 4(N+1/2)$, where $N$ is number of corresponding Landau Level (LL).

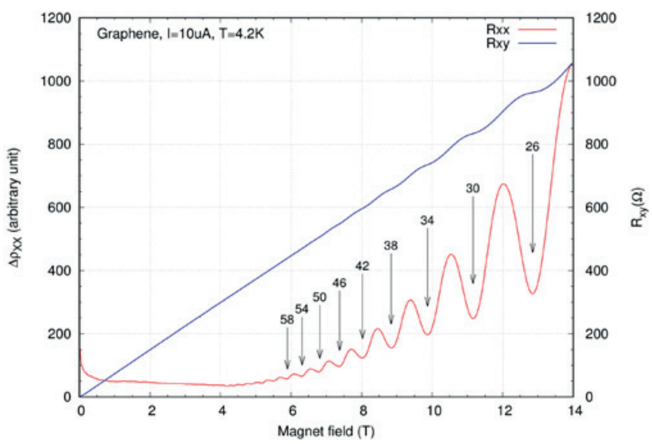


**Fig. 1:** Experimental curves of IQHE and SdH obtained for sample #3084.

The peculiarity of the results obtained is that the plateau of the filling factor v = 58 (corresponding to LL number $N = 14$) is observed on the curve $R_{xy}(B)$ for sample #3084 while for sample #3491 – v=42 ($N = 10$). Interpretation of observed IQHE and SdH performed using the LL energy calculations according the equation $E_N = (2\hbar v_F{}^2 eBN)^{1/2}$, where $v_F$ is the velocity of electrons on the Fermi Level (FL), enabled to determine the FL energy for each sample of graphene, namely: 318 meV for sample #3084 and 312 meV for #3491. These values of FL energy correspond to the electron densities $1.1\cdot10^{13}$ cm$^{-2}$ and $9\cdot10^{12}$ cm$^{-2}$ respectively. In this way, obtained results of IQHE indicate clearly high quality of graphene layers obtained using CVD method on SiC substrates.

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# Strong Anisotropic Spin-Orbit Interaction in Graphene Induced by Transition-Metal Dichalcogenides

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Spin-orbit interaction (SOI) is an essential building block for novel quantum phenomena such as spin Hall effect or topologically nontrivial states. When applied to two dimensional materials, it can drive graphene into the two-dimensional (2D) topological insulator (quantum spin Hall (QSH) insulator) as first pointed out by Kane and Mele [1]. However, intrinsic SOI in graphene is much smaller than the value assumed in this first theoretical study, and it makes difficult to realize the QSH state in graphene. Strong SOI of graphene is also important for graphene spintronics because it enables self-generation and detection of spin currents via the spin Hall effect. Therefore generation of strong SOI in graphene is an important task to progress research on both topological physics and spintronics.

In this study, we demonstrate strong SOI in graphene induced by transition metal dichalcogenides (TMDs). TMDs are two dimensional materials similar to graphene, and they have strong intrinsic SOI due to heavy transition metal elements. Interestingly, they have different band structures depending on the thickness. We fabricated heterostructures with graphene and $WS_2$ by using both monolayer and bulk $WS_2$ to investigate the difference between them in the capacity to induce SOI in neighboring graphene.

To evaluate the amplitudes of the induced SOI in graphene, we performed magneto-transport measurements at low temperatures. While pristine graphene exhibits the weak localization behavior due to the small SOI, graphene on both monolayer and bulk $WS_2$ show weak antilocalization (WAL) peaks, a signature of the strong SOI induced in graphene. Surprisingly, the observed magnetoresistance curves show drastically different shapes between the graphene/monolayer and graphene/bulk $WS_2$ samples. The detailed analysis based on the theoretical formula demonstrates that the induced SOI in graphene is much stronger for graphene/monolayer $WS_2$ samples than for graphene/bulk $WS_2$ ones.

We also investigated the symmetry of the induced SOI. The dominant mirror-symmetric SOI with graphene as a mirror plane is essential to realize the QSH state, thus it is significant to scrutinize the symmetry of the induced SOI. From the theoretical fits of the magneto-transport data, we found that symmetric SOI is much more dominant than the asymmetric one. The symmetric SOI in this system is composed of the two contributions, the intrinsic SOI and valley-Zeeman (VZ) SOI, a unique type of SOI in this system [2]. To determine the dominant type of the SOI in the symmetric contribution, we analyzed the spin relaxation mechanisms. In graphene, the two spin relaxation mechanisms, the Elliot-Yafet (EY) and D'yakonov-Perel mechanisms are possible. The former is caused by the intrinsic SOI, and the latter relevant to the VZ SOI. From the analysis we found that the EY contribution is dominant close to the Dirac point. This result indicates the existence of the intrinsic SOI, essential to realize the QSH state [3].

In our presentation, we also show our experimental results and their analysis on graphene/$WSe_2$ and $MoS_2$ heterostructures. For graphene/$WSe_2$ heterostructures we exploited both monolayer and bulk $WSe_2$ to compare the difference in the induced SOI in graphene. In these systems we also observed the WAL behaviour, a signature of the induced strong SOI. However, the observed magnetoconductivity curves thus the amplitudes of the induced SOI in graphene are strikingly different from each other. We discuss these differences in the amplitudes and also the symmetry of the SOI based on the detailed analysis of the experimental results. Our findings on introduction of SOI in graphene reveal that graphene can be a promising material for both topological physics and spintronics, and pave the way to establish the new role of graphene in these fields.

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# Transition from rhombohedral to Bernal stacking in multilayer graphene induced by lithographic contact patterning

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The properties of graphene flakes with more than one layer are greatly affected by the lateral arrangement of the layers. Multilayer graphene exhibits two most stable stacking configurations, Bernal and rhombohedral, which differ in band structure as well as in magnetic and electronic properties. Both stacking configurations can coexist within a graphene flake, and boundaries between domains can be described as solitons that host topologically protected states. The stability of the stacking domains is still not well understood. Here we show by correlative microscopies, infrared near-field microscopy (s-SNOM) and scanning Raman spectroscopy, that the preparation of metal contacts on 3–7 layer flakes using electron beam lithography can induce a change of stacking from rhombohedral to Bernal. Surprisingly, the reversed transition (Bernal to rhombohedral) was never observed. We discuss compressive and/or shear stress as possible causes for this transition. It appears that rhombohedral stacking is less stable than previously thought as even small influences can alter the arrangement of layers and disturb the balance between the two stacking configurations providing a driving force for a non-reversible transformation.

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# Anomalous reentrant quantum Hall effect in the HgTe/CdHgTe double quantum well

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The uniqueness of the energy spectrum of the HgTe quantum well and its strong dependence on the well width allows us to construct various versions of a nontrivial energy structure in the HgTe/CdHgTe double quantum well (DQW) [1]. This may be useful for a variety of applications, as well as for research of fundamental phenomena in new conditions. For example, in a DQW with relatively wide HgTe layers (20 nm), it is possible to create an enhanced overlap of the conduction and valence subbands that may be controlled by the gate voltage $V_g$ [2]. As a result, the critical field of opening the gap is shifted to higher fields, where it falls into the well-pronounced regime of the quantum Hall effect (QHE). Under these conditions, specific features, such as multiple inversions of QHE and a stable transition into a zero filling factor state, were revealed and explained in terms of the mixed electron and hole nature of magnetic levels.

Especially pronounced anomalies in the structure of QHE were found in the DQW with HgTe layers of critical thickness (6.5 nm) [3]. In this case, the DQW energy spectrum resembles that of a bilayer graphene, but with its own additional features and a possibility to modify it. Here, in the unusual structure of QHE, a combination of two different modes appears on a single magnetoresistance (MR) plot: the one for free holes at high fields, where the 2–1 plateau–plateau transition reacts to $V_g$, and the other for a case of partial localization of holes into the lateral maxima (LM) in the valence subband: in relatively weak fields where the structures indicate a much lower density of mobile holes and are almost insensitive to $V_g$. A transition region between these two modes manifests a reentrant behavior of QHE, since MR returns to the same plateau with varying magnetic field. We show, on the basis of detailed calculations of the energy spectra and the patterns of magnetic levels, that the observed anomalies in QHE are caused by a combination of two factors: a proximity of the Fermi level to LM and the imposition of an electron level on a series of light hole levels. Due to the latter, the gaps between the magnetic levels with certain filling factor numbers ν acquire a peculiar quasi-triangular shape and the Fermi level trace as a function of field may cut the lower corner of such a gap for ν = 1 thus returning to the ν = 1 state in a restricted range of fields. The insensitivity of QHE to $V_g$ at low fields is due to a high density of states in the vicinity of LM, while at higher fields the Fermi level rises in energy to the higher lying hole magnetic levels thus leaving the high density area. Evolution of the observed anomalous structure in MR with $V_g$ was investigated in detail. It was found that the DQW profile is initially asymmetric but it is made symmetric at some positive $V_g$. The experimental picture of the MR evolution with field and $V_g$ contains characteristic points that correspond to specific points in the calculated magnetic level pattern, thus the realistic DQW profile may be corrected so that these features coincide.

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# Quantum Hall states in an anisotropic bulk Weyl semimetal TaAs

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Tantalum Arsenide (TaAs) as the first Weyl Semimetal candidate, is considered as a three dimensional (3D) analogy of graphene upon breaking time-reversal or inversion symmetry. We report the two-dimensional (2D) -like Shubnikov-de Haas (SdH) oscillations accompanied by nearly quantized Hall resistivity of each quantum layer (QL) of four-degenerate Landau fillings, in the high mobility TaAs crystal with *c*- (001) sample surface, where the typical thickness of the quantum layer is 5 nm. More integer quantum Hall (QH) plateaus (at even number fillings) appear in thinner samples. On the other hand, due to the anisotropy of band structure, there is no quantum Hall plateau with the single crystal sample of *a*- (100) crystalline surface. The experiments in the bulk sample may support the theory of quantum Hall effect of Fermi arc. In addition, microwave photovoltage (PV) and photocurrent ($I_{ph}$) present distinct 2D-like quantum oscillations and QH states with high quality features. PV and $I_{ph}$ minima at integer fillings appear at more Landau level fillings, the QH degeneracy is broken further. Microwave enhances the conductivity and mobility within the skin depth (about 300 nm) of the electromagnetic field, thus more QH features are observed.

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