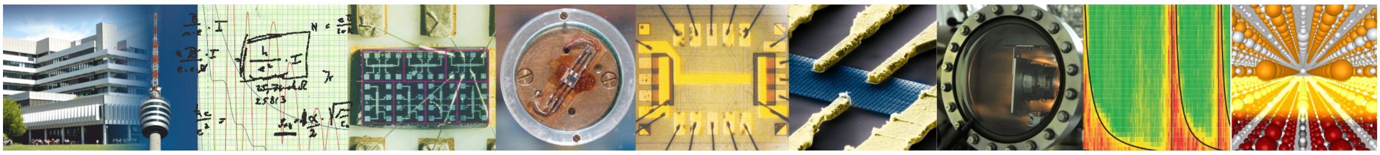
Quantum Hall Effects and Related Topics



International Symposium

Stuttgart, June 26th - 28th, 2013

Max-Planck-Institut
für Festkörperforschung

General Information, Program, and Abstracts

General Information

Purpose

Since its discovery in 1980, the quantum Hall effect became the fertible ground for several of the most fascinating topics in solid state physics. The Symposium will provide the opportunity to see and discuss the status and exciting developments in this field.

Topics

Distinguished invited speakers will give 30 min presentations on selected topics.

Quantum Hall systems
QHE and the new SI units
Growth of state-of-the art 2DES
5/2 quantum Hall state
Exciton condensation in 2D bilayers
Topological insulators
Graphene and other 2D materials
Oxide heterostructures
Quasiparticles in low-dimensional electron systems

Organizers

The Symposium is organized by the Max-Planck-Institut für Festkörperforschung (Stuttgart, Germany).

Program and Organizing Committee

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Symposium Site

Max-Planck-Institut für Festkörperforschung
(Max Planck Institute for Solid State Research)
Heisenbergstr. 1
D-70569 Stuttgart-Büsnau
Germany

http://www.fkf.mpg.de

Symposium Website

http://www.fkf.mpg.de/QHE2013

Invited Speakers

Gerhard **Abstreiter** (Walter-Schottky-Institute, Germany)
Tsuneya **Ando** (Tokyo Institute of Technology, Japan)
Sankar **Das Sarma** (University of Maryland, USA)
Rui-Rui **Du** (Rice University, USA)
Jim **Eisenstein** (California Institute of Technology (Caltech), USA)
Andre **Geim** (University of Manchester, UK)
Moty **Heiblum** (Weizmann Institute of Science, Israel)
Harold **Hwang** (Stanford University, USA)
Jainendra **Jain** (Penn State University, USA)
Jan-Theodoor **Janssen** (National Physical Laboratory, UK)
Masashi **Kawasaki** (University of Tokyo, Japan)
Philip **Kim** (Columbia University, USA)
Allan **MacDonald** (University of Texas at Austin, USA)
Charles **Marcus** (The Niels Bohr Institute, Denmark)
Laurens **Molenkamp** (University of Wuerzburg, Germany)
Koji **Muraki** (NTT Basic Research Laboratories, Japan)
Marek **Potemski** (Grenoble High Magnetic Field Laboratory, France)
Terry **Quinn** (International Bureau of Weights and Measures, France)
Darrell **Schlom** (Cornell University, USA)
Werner **Wegscheider** (ETH Zurich, Switzerland)
Robert **Willett** (Bell Labs, USA)
Qi-Kun **Xue** (Tsinghua University, China)
Amir **Yacoby** (Harvard University, USA)
Shou-Cheng **Zhang** (Stanford University, USA)
Michael **Zudov** (University of Minnesota, USA)

Honorable Chairman

Klaus **v. Klitzing** (MPI for Solid State Research, Stuttgart)

Invited Chairmen

Günther **Bauer** (Universität Linz, Austria)
Klaus **Ensslin** (ETH Zurich, Switzerland)
Chihiro **Hamaguchi** (Osaka University, Japan)
Rolf **Haug** (Universität Hannover, Germany)
Jörg **Kotthaus** (LMU Munich, Germany)
Friedemar **Kuchar** (Universität Leoben, Austria)
Jochen **Mannhart** (MPI for Solid State Research, Germany)
Noburo **Miura** (Tokyo University, Japan)
Dieter **Weiss** (Universität Regensburg, Germany)

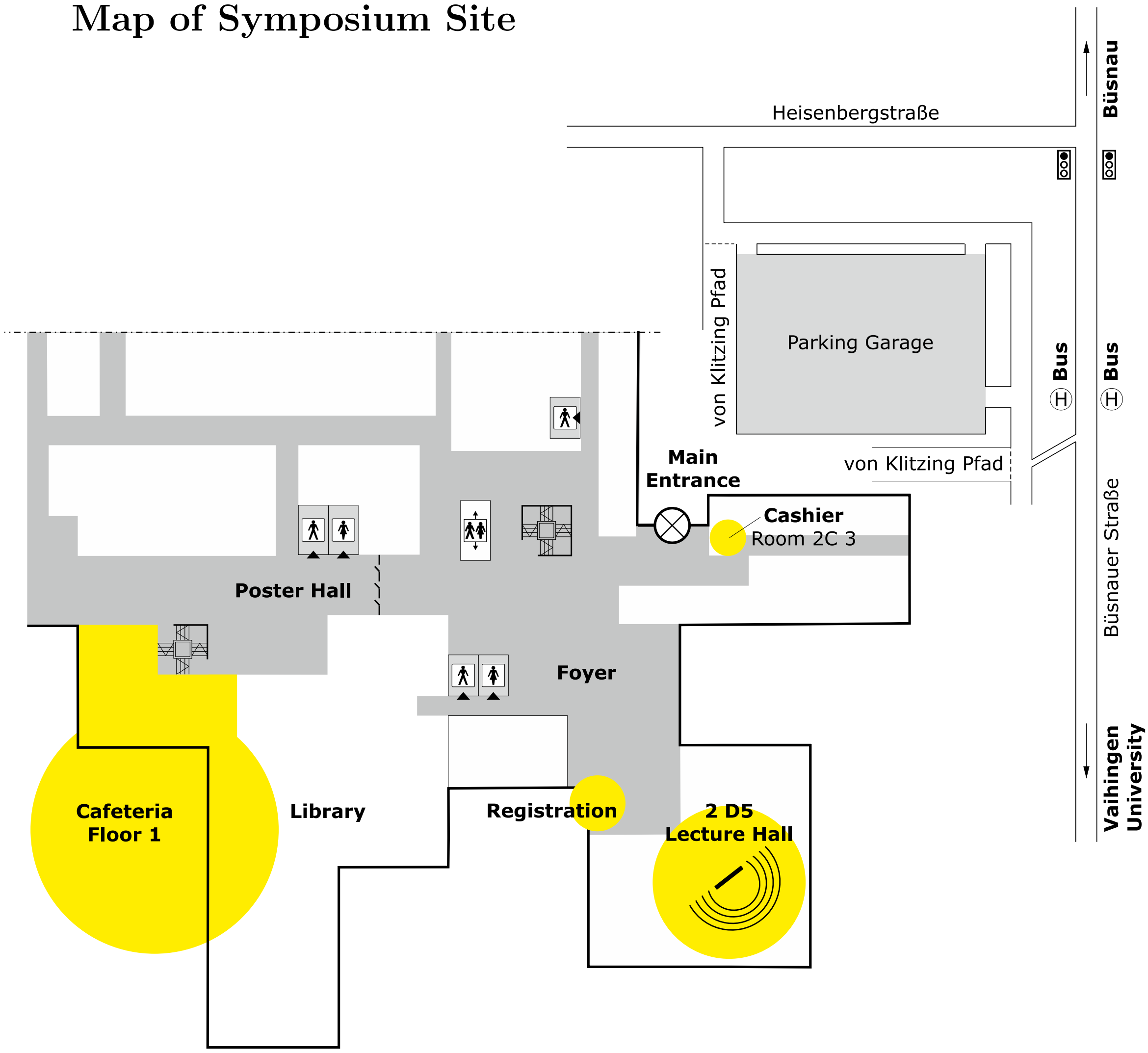
Participants

In addition, about 130 participants have registered for this Symposium, coming from Asia, America and Europe.

Posters

Submitted by participants, about 50 poster contributions have been accepted. The posters will be accessible throughout the whole Symposium.

Map of Symposium Site



WLAN Connection

WLAN (SSID): conference
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Registration Desk

Secretary: Ruth **Jenz**
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Links

Public transportation in Stuttgart: http://www.vvs.de/
Train connections: http://www.bahn.de/
Max Planck Society: http://www.mpg.de/

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 !

Lunches

The lunches on Thursday, June 27th, and Friday, 28th, in the Caferiteria of the MPI are included in the conference fee. There will be three meals and a salad bar.

Reception, Wednesday evening

All invited speakers, chairmen, participants (fee paid) and accompanying persons are invited taking part in the Reception meeting on Wednesday, June 26th, starting at 19:00 in the Cafeteria of the MPI where food and drinks are offered.

Poster Session, Thursday evening

The posters will be accessible throughout the whole Symposium, however on Thurday evening, June 27th, a special poster session is scheduled from 18:00 to 20:00. Beer, wine, soft drinks and fingerfood will be offered close-by. Afterwards, there will be a get-together till 22:00 in the cafeteria and garden of the MPI with beer, wine, soft drinks, bread and cheese.

Symposium Dinner, Friday evening

The Symposium Dinner will take place on Friday evening, June 28th, in Stuttgart downtown at the Restaurant Cube, starting 18:45.

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 Relaxa 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.

Sponsoring

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Program Schedule

Wednesday, June 26th

Time	Event/Location
15:00	Opening of On-Site Registration Coffee, tea, and soft drinks in the Entrance Hall
Welcome 17:00	Lecture Hall Bernhard Keimer Managing Director of the Max-Planck-Institute for Solid State Research Klaus von Klitzing Honorable Chairman of the Symposium
Session 1	Lecture Hall Chair: Friedemar Kuchar
17:15	Terry Quinn **The quantum-Hall effect – the key to the New SI**
17:50	Jan-Theodoor Janssen **Graphene for quantum electrical metrology**
18:25	Andre Geim **Inescapable quantum Hall effect**
19:00-22:00	Welcome Reception with buffet in the Cafeteria

Thursday, June 27th

Session 2	Lecture Hall Chair: Chihiro Hamaguchi
9:00	Tsuneya Ando **Theory of Dirac Electrons in Graphene**
9:35	Allan H. MacDonald **Theory of the Fractional Quantum Hall Effect in Graphene**
10:10	Philip Kim **Hofstadter's Butterfly and interaction driven quantum Hall ferromagnetism in graphene**
10:45	Coffee Break in the Entrance Hall
Session 3	Lecture Hall Chair: Günther Bauer
11:15	Marek Potemski **Magneto-Raman scattering on graphene: Electron-phonon coupling and electronic excitations**
11:50	Amir Yacoby **Fractional quantum Hall effect in graphene**
12:25	Michael Zudov **Nonequlibrium transport in very high Landau levels of quantum Hall systems**
13:00	Lunch in the Cafeteria
Session 4	Lecture Hall Chair: Dieter Weiss
14:30	Jainendra K. Jain **Unconventional quantum Hall effect in the second Λ level.**
15:05	Robert L. Willett **Addressing gaps in the filling factor number line: experiments at even denominator ν**
15:40	Koji Muraki **NMR spectroscopy of FQH-liquid and solid phases in the first and second Landau levels**
16:15	Coffee Break in the Entrance Hall
Session 5	Lecture Hall Chair: Rolf Haug
16:45	Moty Heiblum **Neutral modes in the quantum Hall effect regime**
17:20	Charles Marcus **Interpreting quantum Hall interferometry**
17:55	Conference Photo
18:00	Poster Session in the Poster Hall with beer, wine, and finger food
20:00	Get-Together with beer and wine in the Cafeteria/Garden
22:00	Closing of bar

Friday, June 28th

Session 6	Lecture Hall
	Chair: Jörg Kotthaus
9:00	Shou-cheng Zhang **Quantized anomalous Hall effect in magnetic topological insulators**
9:35	Laurens Molenkamp **HgTe as a Topological Insulator**
10:10	Qi-kun Xue **Experimental realization of quantum anomalous Hall effect in magnetic topological insulator**
10:45	Coffee Break in the Entrance Hall
Session 7	Lecture Hall
	Chair: Klaus Ensslin
11:15	Werner Wegscheider **Engineering of quantum states protected by topology: Perspectives from a crystal growers point of view**
11:50	Rui-Rui Du **Creating Majorana Fermions on the Edge of InAs/GaSb Quantum Wells**
12:25	Sankar Das Sarma **Has the elusive Majorana mode finally been observed in a solid state system?**
13:00	Lunch in the Cafeteria
Session 8	Lecture Hall
	Chair: Jochen Mannhart
14:30	Harold Y. Hwang **2D Superconductors and Bilayers in Oxide Heterostructures**
15:05	Darrell Schlom **Tweaking the Band Structure of Complex Oxides with Strain and Dimensionality**
15:40	Masashi Kawasaki **Quantum Transport at the Polar Oxide Interfaces**
16:15	Coffee Break in the Entrance Hall
Session 9	Lecture Hall
	Chair: Noboru Miura
16:45	Jim Eisenstein **Tunneling and Counterflow Transport in a Bilayer Quantum Hall System**
17:20	Gerhard Abstreiter **40 years of semiconductor physics with Klaus – a reminiscence**
18:00	Busses leaving for Restaurant 'Cube' at downtown
18:45	Reception at the Restaurant
19:15	Conference Dinner
23:00	Busses leaving to Relexa Hotel Schatten and MPI
	End of Symposium

Abstracts PART 1: Invited Talks

The quantum-Hall effect – the key to the New SI

Terry Quinn

Emeritus Director, International Bureau of Weights and Measures, Paris, France

The New SI is a revision of the International System of Units in which each of the seven base units, second, metre, kilogram, ampere, kelvin, mole and candela, will be defined in terms of a fixed numerical value of a fundamental constant or constant of nature. It was adopted in principle by the 24th General Conference on Weights and Measures in 2011 to be implemented when certain experimental data are finally approved. Key to the New SI will be the redefinition of the kilogram in terms of a fixed numerical value for the Planck constant. Such a definition only became possible with the discovery of the quantum-Hall effect.

Graphene for quantum electrical metrology

Jan-Theodoor Janssen

National Physical Laboratory, Teddington, United Kingdom

The discovery of the quantum Hall effect in graphene sparked a lot of excitement in the metrology world because it would allow for the first time a direct comparison of the quantisation in a completely different system with that in conventional semiconductor systems like GaAs or Si. The intrinsic properties of graphene are such that the breakdown current for the QHE is extremely large and in particular in epitaxial graphene a very precise comparison of the value h/e^2 with GaAs has been possible [1]. This has allowed us to test the universality of the QHE to an unprecedented level of accuracy which in turn is important for the pending redefinition of the SI units [2].

Recently we have made the first demonstration of quantised single electron transport through a series of graphene quantum dots [3]. The ability to generate currents via the transfer of single Dirac Fermions in a graphene circuit would potentially extend the range and impact of graphene in a number of key sectors, including digital electronics, quantum information processing, and of course quantum metrology. The pumps operate well at several GHz, enabling them to generate technologically significant currents without compromising heavily on quantisation accuracy. The performance of the pump at such high frequency also outstrips conventional metal and semiconductor adiabatic pumps making them a promising candidate for the realisation of the unit ampere after the redefinition of the SI units.

In this talk I will discuss both the quantum Hall effect in epitaxial graphene and single electron charge pumping through graphene quantum dots and demonstrate the distinct advantages of this material for the future of quantum electrical metrology.

References

[1] A. Tzalenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolillo, M. Syväjärvi, R. Yakimova, O. Kazakova, T.J.B.M. Janssen, V. Fal'ko, S. Kubatkin, Nature Nanotechnology **5**, 186 (2010).

[2] T.J.B.M. Janssen, N.E. Fletcher, R, Goebel, J.M. Williams, A. Tzalenchuk, R. Yakimova, S. Kubatkin, S. Lara-Avilla, and V.I. Fal'ko, New Journal of Physics **13**, 093026 (2011).

[3] M.R. Connolly, K.L. Chiu, S.P. Giblin, M. Kataoka, J.D. Fletcher, C. Chua, J.P. Griffiths, G.A.C. Jones, C.G. Smith, and T.J.B.M. Janssen, arXiv:1207.6597, in press Nature Nanotechnology (2013).

Inescapable quantum Hall effect

Andre Geim

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Theory of Dirac Electrons in Graphene

Tsuneya Ando

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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 $\mathbf{k}$ is rotated around the origin and therefore has a topological singularity at $\mathbf{k} = 0$. This singularity is the origin of the peculiar behavior in transport properties of graphene, such as the minimum conductivity at the Dirac point, the half- integer quantum Hall effect, the dynamical conductivity, crossover between weak- and anti-localization, and a very singular diamagnetic response.

In this talk, exotic electronic and transport properties of graphene [1-7] are reviewed from a theoretical point of view. The subjects include the universal minimum conductivity at the Dirac point for scatterers with potential range shorter than the electron wavelength, its nonuniversal dependence on the disorder strength for long-range scatterers, the weak-field Hall conductivity and its deviation from the Boltzmann result when the potential range is larger than the Fermi wavelength.

Twisted bilayer graphene is currently attracting attention both theoretically and experimentally. Carbon nanotubes are a graphene sheet rolled into a cylindrical form and their electronic states are obtained by imposing periodic boundary conditions or by discretizing the wave vector in the circumference direction. Twisted bilayer ribbons are realized by collapsing thick carbon nanotubes, whose electronic states are also discussed.

References

[1] T. Ando, J. Phys. Soc. Jpn. **75**, 074716 (2006).
[2] T. Fukuzawa, M. Koshino, and T. Ando, J. Phys. Soc. Jpn. **78**, 094714 (2009).
[3] A. Toyoda and T. Ando, J. Phys. Soc. Jpn. **79**, 094708 (2010).
[4] M. Noro, M. Koshino, and T. Ando, J. Phys. Soc. Jpn. **79**, 094713 (2010).
[5] M. Noro, M. Koshino, and T. Ando, J. Phys. Soc. Jpn. **80**, 114701 (2011).
[6] T. Ando, J. Phys. Soc. Jpn. **80**, 014707 (2011).
[7] T. Ando, J. Phys.: Conf. Ser. **302**, 012015 (2011).

Theory of the Fractional Quantum Hall Effect in Graphene

Inti Sodemann and A.H. MacDonald

Physics Department, University of Texas at Austin, Austin TX 78712, USA

Early experimental studies of the fractional quantum Hall effect within the $N = 0$ Landau level of graphene suggest that gaps are larger for filling factors $|\nu| < 1$ than for filling factors $|\nu| > 1$. The property that gaps are relatively small compared to the GaAs case for nearly empty and nearly full $N = 0$ levels is naturally explained [1] by the presence in the graphene case of an ungapped valley degree-of-freedom. When the Hamiltonian is invariant under rotations in valley space, large area skyrmion textures in the valley polarization field are expected to lead to low-energy gapped excitations. I will explain why[2] short-range valley-dependent contributions to the Hamiltonian increase excitation energies for $|\nu| < 1$, but not for $|\nu| > 1$.

References

[1] A.H. MacDonald and J.J. Palacios, Phys. Rev. B. **58**, R10171 (1998).

[2] Inti Sodemann and A.H. MacDonald, arXiv:1306.nnnn.

Hofstadter's Butterfly and interaction driven quantum Hall ferromagnetism in graphene

Philip Kim

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Electrons moving in a periodic electric potential form Bloch energy bands where the mass of electrons are effectively changed. In a strong magnetic field, the cyclotron orbits of free electrons are quantized and Landau levels forms with a massive degeneracy within. In 1976, Hofstadter showed that for 2-dimensional electronic system, the intriguing interplay between these two quantization effects can lead into a self-similar fractal set of energy spectrum known as Hofstadter's Butterfly.

Experimental efforts to demonstrate this fascinating electron energy spectrum have continued ever since. Recent advent of graphene, where its Bloch electrons can be described by Dirac feremions, provides a new opportunity to investigate this half century old problem experimentally.

In this presentation, I will discuss the experimental realization Hofstadters Butterfly via substrate engineered graphene under extremely high magnetic fields controlling two competing length scales governing Dirac-Bloch states and Landau orbits, respectively. In addition, the strong Coulomb interactions and approximate spin-pseudo spin symmetry are predicted to lead to a variety of integer quantum Hall ferromagnetic and fractional quantum Hall states and the quantum phase transition between them in graphene. I will discuss several recent experimental evidences to demonstrate the role of the electron interaction in single and bilayer graphene.

Magneto-Raman scattering from graphene: Electron-phonon coupling and electronic excitations

Marek Potemski

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The results of magneto-Raman scattering experiments on graphenes which can be found on graphite surfaces or those deposited on Si/SiO_2 or h-BN substrates will be reviewed. A rich spectrum of magneto-phonon resonances which imply phonons from Γ - as well as K-point of the Brillouin zone of graphene will be reported and purely electronic response in Raman scattering spectra will be demonstrated. The experiment data are in overall agreement with the existing theoretical models, but at the same time reveal new, subtle effects related to electron-phonon and possibly electron-electron interactions: resonances of two-particle excitations, changes in the Fermi velocity. A phenomenological interpretation of these latter observations will be suggested. An evolution of the magneto-Raman scattering response with doping and in multi-layer graphene (bilayer, quadri-layer, graphite) will be also discussed.

References

[1] Tuning the Electron-Phonon Coupling in Multilayer Graphene with Magnetic Fields, C. Faugeras, M. Amado, P. Kossacki, M. Orlita, M. Sprinkle, C. Berger, W. A. de Heer, and M. Potemski, Phys. Rev. Lett. **103**, 186803 (2009).

[2] Magneto-Raman Scattering of Graphene on Graphite: Electronic and Phonon Excitations,
C. Faugeras, M. Amado, P. Kossacki, M. Orlita, M. Khne, A. A. L. Nicolet, Yu. I. Latyshev, and M. Potemski, Phys. Rev. Lett. **107**, 036807 (2011).

[3] How Perfect Can Graphene Be?,
P. Neugebauer, M. Orlita, C. Faugeras, A.-L. Barra, and M. Potemski,
Phys. Rev. Lett. **103**, 136403 (2009).

[4] Circular dichroism of magnetophonon resonance in doped graphene,
P. Kossacki, C. Faugeras, M. Khne, M. Orlita, A. Mahmood, E. Dujardin, R. R. Nair, A. K. Geim, and M. Potemski, Phys. Rev. **B 86**, 205431 (2012).

[5] Polarization-resolved magneto-Raman scattering of graphene-like domains on natural graphite, M. Khne, C. Faugeras, P. Kossacki, A. A. L. Nicolet, M. Orlita, Yu. I. Latyshev, and M. Potemski, Phys. Rev. **B 85**, 195406 (2012).

[6] Electronic excitations and electron-phonon coupling in bulk graphite through Raman scattering in high magnetic fields,
P. Kossacki, C. Faugeras, M. Khne, M. Orlita, A. A. L. Nicolet, J. M. Schneider, D. M. Basko, Yu. I. Latyshev, and M. Potemski, Phys. Rev. **B 84**, 235138 (2011).

[7] Probing the band structure of quadri-layer graphene with magneto-phonon resonance,
C. Faugeras, P. Kossacki, A. A. L. Nicolet, M. Orlita, M. Potemski, A. Mahmood and D.M. Basko, New J. Phys. **14**, 095007 (2012).

Fractional quantum Hall effect in graphene

Amir Yacoby

Harvard University, Department of Physics, Cambridge MA 02138, USA

Graphene and its multilayers have attracted considerable interest owing to the fourfold spin and valley degeneracy of their charge carriers, which enables the formation of a rich variety of broken-symmetry states and raises the prospect of controlled phase transitions among them. In especially clean samples, electron-electron interactions were recently shown to produce surprising patterns of symmetry breaking and phase transitions in the integer quantum Hall regime. Although a series of robust fractional quantum Hall states was also recently observed in graphene, their rich phase diagram and tunability have yet to be fully explored. Here we report local electronic compressibility measurements of ultraclean suspended graphene that reveal a multitude of fractional quantum Hall states surrounding filling factors $\nu = -1/2$ and $-1/4$. In several of these states, we observe phase transitions that indicate abrupt changes in the underlying order and are marked by a narrow region of negative compressibility that cuts across the incompressible peak. Remarkably, as filling factor approaches $\nu = -1/2$, we observe additional oscillations in compressibility that appear to be related to the phase transitions and persist to within 2.5 % of $\nu = -1/2$. We use a simple model based on crossing Landau levels of composite particles with different internal degrees of freedom to explain many qualitative features of the experimental data. Our results add to the diverse array of correlated states observed in graphene and demonstrate substantial control over their order parameters, showing that graphene serves as an excellent platform to study correlated electron phases of matter.

Nonequlibrium transport in very high Landau levels of quantum Hall systems

Michael Zudov[1], Anthony Hatke[1], John Watson[2], Michael Manfra[2], Loren Pfeiffer[3], and Kenneth West[3]

[1]University of Minnesota, Minneapolis, Minnesota, USA
[2]Purdue University, West Lafayette, Indiana, USA
[3]Princeton University, Princeton, New Jersey, USA

The discovery of microwave- [1], phonon- [2], and Hall field- [3] induced resistance oscillations, as well as microwave-induced zero-resistance states [4] and dc field-induced zero-differential resistance states [5] in high mobility 2D electron systems (2DES) has launched an exciting research field of nonequilibrium quantum transport [6]. More recently, giant microwave photoresistance effects have been discovered near both the first [7] and the second [8] harmonics of the cyclotron resonance.

This talk will give an overview of such nonequilibrium phenomena and discuss some of our recent findings. In one experiment [9], we have employed resistively detected magnetoplasmon resonance as a probe of absolute negative conductivity associated with zero-resistance states. In another study [10], we have shown that the electron effective mass obtained from microwave-induced resistance oscillations is significantly lower that the one obtained from the magnetoplasmon resonance, possibly indicating importance of electron-electron interaction effects. Finally, the talk will report on a new resonant structure in microwave photoresistance near the cyclotron resonance which emerges at high radiation frequencies.

References

[1] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, arXiv:cond-mat/9711149 (1997); Phys. Rev. B **64**, 201311(R) (2001).

[2] M. A. Zudov, I. V. Ponomarev, A. L. Efros, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **86**, 3614 (2001).

[3] C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002).

[4] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Nature **420**, 646 (2002); M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 046807 (2003); S. I. Dorozhkin, L. N. Pfeiffer, K. W. West, K. von Klitzing, and J. H. Smet, Nature Physics **7**, 336 (2011).

[5] A. A. Bykov, J.-Q Zhang, S. Vitkalov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. Lett. **99**, 116801 (2007); A. T. Hatke, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **82**, 041304(R) (2010).

[6] I. A. Dmitriev, A. D. Mirlin, D. G. Polyakov, and M. A. Zudov, Rev. Mod. Phys. **84**, 1709 (2012).

[7] J. H. Smet, B. Gorshunov, C. Jiang, L. N. Pfeiffer, K. W. West, V. Umansky, M. Dressel, R. Meisels, F. Kuchar, and K. von Klitzing, Phys. Rev. Lett. **95**, 116804 (2005).

[8] Y. Dai, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **105**, 246802 (2010); A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 121301(R) (2011); Phys. Rev. B **83**, 201301(R) (2011); Y. Dai, K. Stone, I. Knez, C. Zhang, R. R. Du, C. Yang, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **84**, 241303(R) (2011).

[9] A. T. Hatke, M. A. Zudov, J. D. Watson, and M. J. Manfra, Phys. Rev. B **85**, 121306(R) (2012).

[10] A. T. Hatke, M. A. Zudov, J. D. Watson, M. J. Manfra, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **87**, 161307(R) (2013).

Unconventional quantum Hall effect in the second Λ level

Jainendra K. Jain

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The nature of the fractional quantum Hall effect depends sensitively on the interaction pseudopotentials, which, for example, is responsible for interesting new physics in the second Landau level. We show[1, 2] that remarkable new structures arise also in the second composite-fermion Landau level (Λ level) because of a peculiar interaction between composite fermions that primarily penalizes composite fermion pairs with relative angular momentum 3. We focus on composite fermion filling factors $\nu^* = 1 + 1/3, 1 + 2/3$ and $1 + 1/2$, which manifest as 4/11, 5/13 and 3/8 of electrons; evidence for fractional quantum Hall effect at these fractions was seen by Pan *et al.* more than a decade ago [3]. In Ref. [2] we provide compelling evidence that the 1/3 and 2/3 states of composite fermions in the second Λ level are topologically distinct from the familiar 1/3 and 2/3 states, thus demonstrating that the electronic fractional quantum Hall effect at 4/11 and 5/13 represents an unconventional order, arising from a new mechanism of incompressibility not realized elsewhere. This study resolves the controversy surrounding the origin of these states in favor of the proposal of Wójs, Yi and Quinn[4]. In addition, we show [1] that an incompressible state at 3/8 is very likely a chiral p-wave paired state of composite fermions of the anti-Pfaffian kind. Several concrete predictions for experiments follow from this physics.

References

[1] S. Mukherjee, S. S. Mandal, A. Wójs, J. K. Jain, "Possible anti-pfaffian pairing of composite fermions at $\nu = 3/8$," *Phys. Rev. Lett.* **109**, 256801 (2012).

[2] S. Mukherjee, S. S. Mandal, A. Wójs, J. K. Jain, "Unconventional Fractional Quantum Hall Effect at $\nu = 4/11$ and 5/13," unpublished.

[3] W. Pan, H.L. Stormer, D. C. Tsui, L.N. Pfeiffer, K.W. Baldwin, K. W. West, "Fractional quantum Hall effect of composite fermions," *Phys. Rev. Lett.* **90**, 016801 (2003).

[4] A. Wójs, K.-S. Yi, J.J. Quinn, "Fractional quantum Hall states of clustered composite fermions," *Phys. Rev. B* **69**, 205322 (2004).

Addressing gaps in the filling factor number line: experiments at even denominator ν

Robert Willett

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Even denominator filling factors were relative ‘late bloomers’ in the quantum Hall effect world. We will discuss non-exhaustively experiments at these quantum numbers.

NMR Spectroscopy of FQH Liquid and Solid Phases in the First and Second Landau Levels

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Nuclear magnetic resonance (NMR) has been widely used to explore the physics in the quantum Hall systems associated with the spin degree of freedom. Recently, resistively detected NMR measurements have demonstrated the full spin polarization of the $\nu = 5/2$ quantum Hall state [1, 2]. Interestingly, the system remains fully polarized throughout the second Landau level, including not only the quantized Hall states at $\nu = 5/2$, 7/3, and 8/3, but also the non-quantized states between them [1]. I will discuss the implications of this behavior and the possibility to experimentally observe active roles of spin at and around $\nu = 5/2$.

Furthermore, I will show that NMR is a powerful tool to study not only the spin, but also the charge degree of freedom in the electron system. This becomes relevant when the electron system enters a phase that breaks the in-plane translational symmetry. We observe striking anomalies in the Knight shift and spectral lineshape that appear at low partial filling of both the first and second Landau levels. Numerical simulations using the wave function of a Hartree-Fock Wigner crystal reproduce the observed anomalies exceedingly well. By virtue of the spatial resolution provided by the nuclear spins, which serve as built-in local probes, we are able to resolve the quantum and thermal fluctuations of lattice electrons and quantify the deviation from the $T = 0$ Hartree-Fock Wigner crystal.

K. M. thanks L. Tiemann, T. D. Rhone, G. Gamez, N. Kumada, and N. Shibata for their collaboration in this work.

References

[1] L. Tiemann, G. Gamez, N. Kumada, and K. Muraki, Science **335**, 828 (2012).

[2] M. Stern, B. A. Piot, Y. Vardi, V. Umansky, P. Plochocka, D. K. Maude, and I. Bar-Joseph, Phys. Rev. Lett. **108**, 066810 (2012).

Neutral modes in the quantum Hall effect regime

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Current propagates in the quantum Hall regime along the edges of a two-dimensional electron gas via 'downstream' chiral edge modes. In the fractional regime, for some fractional states - the so called 'holes-conjugate' states, i.e., between filling factors $n+1/2$ and $n+1$ - early predictions suggested, that due to edge reconstruction, each 'downstream' chiral mode is accompanied by an 'upstream' chiral mode (opposite chirality). Since experiments did not find 'upstream' chiral edge modes, it had been proposed that in the presence of interactions and disorder the 'downstream' charge modes are accompanied by 'upstream' neutral mode - with the latter carrying energy without net charge - explaining thus why the 'upstream' modes were not detected thus far. Moreover, a neutral 'upstream' mode is also expected for selected wavefunctions, which were proposed for the 'even denominator' state 5/2.

I will review some of our observations of neutral modes in selected quantum Hall states. Neutral mode detection was performed by allowing it to impinge on a QPC constriction or at an ohmic contact. Partitioning of the neutral mode, or heating of the charge mode, led to excess current fluctuations propagating 'downstream'. The main observed effects are: (a) Resultant current noise, being proportional to the applied voltage on the injecting contact, however, without a net current; (b) Partitioning charge modes in a QPC excited an 'upstream' neutral mode; (c) The neutral mode decays with length and temperature; (d) An upstream neutral mode was observed for the 5/2; likely singling out the anti-Pfaffian wavefunction for the e/4 quasiparticles; (e) Impinging the neutral mode on a QD led to a thermo-electric net current, with a broadened conductance peak (indicating heating).

Interpreting quantum Hall interferometry

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Transport in the integer and fractional quantum Hall regimes through quantum dots and antidots show periodic modulation as a function of field and gate voltage. The oscillations can arise from various physical mechanisms, and depending on the mechanism lead to different interpretations, for instance in terms of fractional charge. This talk will review resent experimental results in terms of these alternative mechanisms.

The talk will focus on the experimental results reported in A. Kou et al. and D. T. McClure, et al. but will attempt to place these results into a broader context.
Research supported by Microsoft through Project Q, the Department of Energy, Harvard University, and the Danish National Research Foundation.

Quantized anomalous Hall effect in magnetic topological insulators

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Discovery of the quantum spin Hall effect and topological insulator has inspired us to theoretically predict the quantized anomalous Hall (QAH) effect in magnetic topological insulators without external magnetic field. Recently this effect has been experimentally discovered in Cr doped topological insulator $(BiSb)_2Te_3$.

In this talk, I shall discuss the theory and experiment of the QAH.

HgTe as a Topological Insulator

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HgTe is a zincblende-type semiconductor with an inverted band structure. While the bulk material is a semimetal, lowering the crystalline symmetry opens up a gap, turning the compound into a topological insulator.

The most straightforward way to do so is by growing a quantum well with (Hg,Cd)Te barriers. Such structures exhibit the quantum spin Hall effect, where a pair of spin polarized helical edge channels develops when the bulk of the material is insulating. Our transport data [1-3] provide very direct evidence for the existence of this third quantum Hall effect, which now is seen as the prime manifestation of a 2-dimensional topological insulator.

To turn the material into a 3-dimensional topological insulator, we utilize growth induced strain in relatively thick (ca. 100 nm) HgTe epitaxial layers. The high electronic quality of such layers allows a direct observation of the quantum Hall effect of the 2-dimensional topological surface states [4]. These states appear to be decoupled from the bulk. This allows us to induce a supercurrent is induced in the surface states by contacting these structures with Nb electrodes [5].

References

[1] M. König et al., Science **318**, 766 (2007).
[2] A. Roth *et al.*, Science **325**, 294 (2009).
[3] C. Brüne *et al.*, Nature Physics **8**, 486 (2012).
[4] C. Brüne *et al.*, Phys. Rev. Lett. **106**, 126803 (2011).
[5] L. Maier *et al.*, Phys. Rev. Lett. **109**, 186806 (2012);
J. Oostinga et al., PRX, to be published.

Experimental realization of quantum anomalous Hall effect in magnetic topological insulator

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Anomalous Hall effect (AHE) was discovered by Edwin Hall in 1880. In this talk, we report the experimental observation of the quantized version of AHE, the quantum anomalous Hall (QAH) effect in thin films of Cr-doped $(Bi,Sb)_2Te_3$ magnetic topological insulator. At zero magnetic field, the gate-tuned anomalous Hall resistance exhibits a quantized value of h/e^2 accompanied by a significant drop of the longitudinal resistance. The longitudinal resistance vanishes under a strong magnetic field whereas the Hall resistance remains at the quantized value. The realization of the QAH effect paves a way for developing low-power-consumption electronics.

This work was carried out in collaboration with Ke He, Yayu Wang, Xucun Ma, Xi Chen, Jinfeng Jia, Li Lu, Lili Wang, Shuaihua Ji, Zhong Fang, Xi Dai, and Shoucheng Zhang.

Engineering of quantum states protected by topology: Perspectives from a crystal growers point of view

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The theoretical proposal of a novel class of particles that are their own anti-particles Majorana fermions has stimulated research ranging from neutrino physics to dark matter searches. However, recent advances in the synthesis of low-dimensional semiconductor structures allow for the realization of this elusive class of objects also in the condensed matter domain. This talk will survey the current status in molecular beam epitaxy applied for the preparation of heterostructures, which host non-Abelian anyons as excitations in the fractional quantum Hall regime. In addition, tunable two-dimensional topological insulators based on inverted electron-hole bilayer systems in InAs/GaSb coupled quantum wells will be presented. Although these phenomena are currently at the verge of being detectable, they might serve to overcome one of the main obstacles in quantum computing, the decoherence of quantum states, by topological protection.

Creating Majorana Fermions on the Edge of InAs/GaSb Quantum Wells

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In our quest of Majorana femions in condensed matter, superconductor-proximity coupled 1D quantum wires ('Majorana wires') represent a promising system. The requirements for materials quality, however, are rather stringent: among the least of them the wires must be pure and uniform enough, such that the occupied number of modes will be the same over at least several micrometers length. We demonstrate here, by research of Rice group and collaborators, that in inverted InAs/GaSb semiconductor quantum wells these requirements can be readily met by creating and gating the helical edge states. Single mode, spin polarized edges with coherent length over 5 micrometers are routinely observed at liquid helium temperature. This recent materials breakthrough, together with the fact that highly transparent interfaces can be formed between InAs/GaSb and metallic superconductors, opens a well-controlled way of creating and manipulating Majoranas in the lab.

References

[1] Ivan Knez, Rui-Rui Du, and Gerald Sullivan, Phys. Rev. Lett. **107**, 136603 (2011); **109**, 186603 (2012).

Has the elusive Majorana mode finally been observed in a solid state system?

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2D Superconductors and Bilayers in Oxide Heterostructures

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$SrTiO_3$ is a low density bulk superconductor, which when incorporated in heterostructures provides an opportunity for band-structure engineering this superconducting semiconductor. We take this opportunity by selectively doping a channel of finite thickness in an undoped matrix, which is analogous to δ-doping in semiconductors. By varying the thickness of a Nb doped channel, we have studied the crossover from 3D to 2D in the superconducting and normal state properties, as the thickness of the doped layer is decreased [1-4]. A notable feature of these structures is that the mobility strongly increases in the 2D limit [2]. This aspect suggests that a new regime of 2D superconducting phase transitions can be experimentally accessed approaching the clean limit [3]. By the growth of two such δ-doped layers, with variable interlayer spacing, a clear tunable coupling is demonstrated in both the normal-state and superconducting properties [5]. This bi-layer degree of freedom provides an avenue for engineering multi-component superconductivity.

References

[1] Y. Kozuka, M. Kim, C. Bell, B. G. Kim, Y. Hikita, and H. Y. Hwang, Nature **462**, 487 (2009).

[2] Y. Kozuka, M. Kim, H. Ohta, Y. Hikita, C. Bell, and H. Y. Hwang, Appl. Phys, Lett. **97**, 222115 (2010).

[3] M. Kim, C. Bell, Y. Kozuka, M. Kurita, Y. Hikita, and H. Y. Hwang, Phys. Rev. Lett. **107**, 106801 (2011).

[4] M. Kim, Y. Kozuka, C. Bell, Y. Hikita, and H. Y. Hwang, Phys. Rev. **B 86**, 085121 (2012).

[5] H. Inoue, M. Kim, C. Bell, Y. Hikita, and H. Y. Hwang, in preparation.

Tweaking the Band Structure of Complex Oxides with Strain and Dimensionality

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Using epitaxy and the misfit strain imposed by an underlying substrate, it is possible to strain thin films of complex oxides to percent levels far beyond where they would crack in bulk. Under such strains, the band structure of complex oxides can be dramatically altered. Another way of altering the electronic structure is through dimensional confinement, e.g., by confining a material to be a thin layer or by confining it as repeating thin layers within a superlattice. In this talk results from three systems exhibiting metal-insulator transitions brought about by strain or dimensional confinement will be shown: (1) strained $La_{0.7}Sr_{0.3}MnO_3$ [1], (2) $(LaMnO_3)_{2n}$ / $(SrMnO_3)_n$ superlattices [2], and (3) $LaNiO_3$ thin films with thickness as thin as a single unit cell [3]. The films are made by reactive molecular-beam epitaxy (MBE) and their electronic structure is measured on the pristine surface of the as-grown films by angle-resolved photoemission spectroscopy (ARPES). We use ARPES to track how the momentum-resolved electronic structure evolves through the strain or dimensionality driven metal-insulator transition. In all three cases our results are consistent with an ordering instability mechanism, in which electronic charge ordering or orbital ordering is responsible for the loss of the metallic state.

This work was done in collaboration with the groups of Kyle Shen (Physics), David A. Muller (Applied and Engineering Physics), and Richard G. Hennig (Materials Science and Engineering) all at Cornell University, and Reinhard Uecker at the Leibniz Institute for Crystal Growth. The contributing coauthors are listed in Refs. [1]-[3].

References

[1] E.J. Monkman, C. Adamo, D.E. Shai, D.W. Shen, J.W. Harter, C.M. Brooks, M. Bernhagen, R. Uecker, I.S. Elfimov, R.G. Hennig, D.G. Schlom, and K.M. Shen (unpublished).

[2] E.J. Monkman, C. Adamo, J.A. Mundy, D.E. Shai, J.W. Harter, D. Shen, B. Burganov, D.A. Muller, D.G. Schlom, and K.M. Shen, 'Quantum Many-Body Interactions in Digital Oxide Superlattices', Nature Materials **11**, 855-859 (2012).

[3] P.D.C. King, E.J. Monkman, D.E. Shai, J.W. Harter, C. Adamo, D.G. Schlom, and K.M. Shen (unpublished).

Quantum Transport in Polar Oxide Heterostructures

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We present our recent progress on the two dimensional electron systems created at oxide heterostructures. ZnO is a semiconductor that has a wide bandgap of 3.3 eV with a polar Wurzite crystal structure. The bandgap can be tuned to 4.3 eV with making an alloy of $Mg_xZn_{1-x}O$ upto $x = 0.5$. At the same time, spontaneous polarization (P) along its polar axis is also tuned, larger x, larger P, due to the gradual deformation of crystal structure from tetrahedral to octahedral coordination at the Mg site (same as that in rock salt MgO). The discontinuity in P at the MgZnO/ZnO heterointerface is compensated with the accumulation of two dimensional electron systems in the narrower bandgap of ZnO.

Continuing effort in making higher quality heterostructures has enabled us to observe integer quantum Hall effect (QHE), fractional QHE, lowest Landau levels, metal insulator transitions, quantum Hall ferromagnet, and other intriguing properties for samples with a mobility exceeding 700,000 cm^2/Vs.

The talk will overview the motivation and progress of our work with a highlight of strong correlation effect that may not be easy to realize in other two dimensional systems.

References

[1] A.Tsukazak *et al.*, Science **315**, 1388 (2007).
[2] A.Tsukazaki *et al.*, Nature Mater. **9**, 889 (2010).
[3] Y. Kozuka *et al.*, Phys. Rev. B **84**, 033304 (2011).
[4] J. Falson *et al.*, Appl. Phys., Express, **4**, 090011 (2011).
[5] Y. Kozuka *et al.*, Phys. Rev. B **85**, 075302 (2012).
[6] D. Maryenko *et al.*, Phys. Rev. Lett. **108**, 186803 (2012).
[7] Y. Kozuka *et al.*, J. Appl. Phys. **112**, 043515 (2012).
[8] Y. Kasahara *et al.*, Phys. Rev. Lett. **109**,246401 (2012).
[9] Y. Kozuka *et al.*, Phys. Rev. **B 87**, 205411 (2013).
[10] Posters by Joseph Falson and Denis Maryenko in this workshop.

Tunneling and Counterflow Transport in a Bilayer Quantum Hall System

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Like all quantum Hall systems, a bilayer 2D electron system at total filling factor $\nu_T = 1$ possesses an energy gap to charged quasiparticle excitations. However, the $\nu_T = 1$ bilayer is (so far) unique in also possessing a low energy condensate capable of transporting energy independent of the charged quasiparticles. The condensate may be viewed as a phase coherent ensemble of interlayer excitons, broadly analogous to the Cooper pair condensate in a superconductor. Excitons, being charge neutral, are not subject to a Lorentz force and are thereby free to move throughout the bulk of the 2D system.

Coupling to the condensate requires probes which are antisymmetric in the layer degree of freedom. The focus of this talk will therefore be on our recent interlayer tunneling and counterflow transport measurements [1, 2, 3], both of which meet this antisymmetry requirement.

It has been long known that interlayer tunneling at $\nu_T = 1$ resembles the dc Josephson effect in superconducting tunnel junctions. Our recent results clearly demonstrate that extrinsic resistances in the tunneling circuit are responsible for the instabilities and hysteresis often observed in strongly tunneling samples, but fortunately do not appear to interfere with the identification of a maximum or critical tunneling current, I_c. Interestingly, we find evidence for a "universal" temperature dependence of the critical current.

Making use of a Corbino annular geometry, first applied to the $\nu_T = 1$ problem by the Stuttgart group [4], our counterflow measurements have shown that neutral excitons within the condensate are free to move across the insulating bulk of the quantum Hall system even when ordinary charge transport is heavily suppressed. As expected, we find that at higher temperatures, drive levels, and layer separations charged quasiparticle transport competes with the condensate transport and that simple modeling captures this competition.

Finally, if time permits, the question of dissipation in the condensate channel will also be briefly discussed.

This contribution reflects a collaboration with A.D.K. Finck, D. Nandi, T. Khaire, L.N. Pfeiffer, and K.W. West and is supported by NSF grant DMR-1003080.

References

[1] A.D.K. Finck, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, Phys. Rev. Lett. **106**, 236807 (2011).
[2] D. Nandi, A.D.K. Finck, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, Nature **488**, 481 (2012).
[3] D. Nandi, T. Khaire, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, in preparation.
[4] L. Tiemann, J.G.S. Lok, W. Dietsche, K. von Klitzing, K. Muraki, D. Schuh, and W. Wegscheider, Phys. Rev. B **77**, 033306 (2008).

Abstracts - PART 2: Posters

Imaging Integer and Fractional Quantum Hall Edge States

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We present scanning gate microscopy (SGM) measurements on a quantum point contact (QPC) patterned on top of a high-mobility two-dimensional electron gas (2DEG) in a GaAs-AlGaAs heterostructure. The measurements are carried out at a temperature of 100 mK in a strong perpendicular magnetic field. A local potential perturbation induced by the voltage-biased tip of the microscope is used to probe the underlying 2DEG [1]. The tip acts as a movable gate. Depending on its position, quantum Hall edge channels can be selectively transmitted or reflected [2, 3]. Thus, as a function of tip-position stripes of constant filling factors are resolved. Even filling factors appear as very pronounced plateaus in the maps of the conductance as a function of tip position, as seen in fig. 1a). Odd filling factors can be seen as smaller stripes. At very high magnetic fields we can observe very distinct signatures of fractional filling factors 1b), c), d).

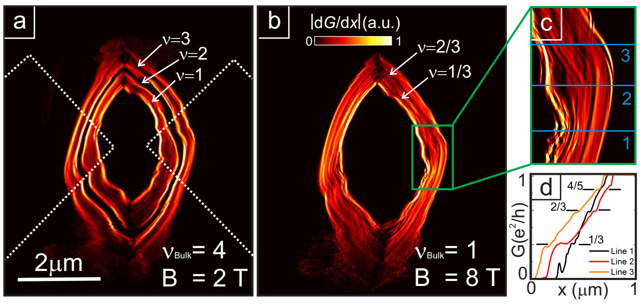

Figure 1: a) SGM image taken at a filling factor of 4 in the bulk. Plateaus at values of 3, 2 and 1 e^2/h can be observed. Dashed lines show the outline of the QPC. b) Same image at a filling factor of 1 in the bulk. Black stripes show filling factors of 1/3 and 2/3. c) Zoom at the position of the green frame in b). Especially in d) clear plateaus at filling factors 1/3, 2/3 and 4/5 are visible.

The measurements give a direct measure for the real space behavior and distribution of quantum Hall edge channels. Putting our results into a theoretical framework we can draw conclusions about the alternating compressible and incompressible stripes, which are formed in the quantum Hall regime [4]. The measurements show the fragile nature of fractional quantum Hall effect edge states and their behavior in the local potential landscape.

References

[1] N. Paradiso, S. Heun, S. Roddaro, L. Sorba, F. Beltram, G. Biasiol, L.N. Pfeiffer and K.W. West, PRL **108**, 246801 (2012).

[2] B. I. Halperin, PRB **25**, 2185 (1982).

[3] M. Büttiker, PRB **41**, 7906 (1988).

[4] D. B. Chklovskii, B. I. Shklovskii and L. I. Glazman, PRB **46**, 4026 (1992).

Ballistic Interference in Ultraclean Suspended Graphene

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We have fabricated suspended monolayer graphene devices on organic lift-off resists. We have extended this technology, which was introduced by N. Tombros et al. [1], allowing to add a multitude of bottom and top gates. Using in-situ current annealing [2], we show that exceptionally high mobililties can be obtained in these devices approaching values of $100\,\mathrm{m}^2/\mathrm{Vs}$. Specifically, we have studied the two terminal transport of ultraclean monolayer graphene whose electrostatic potential can be tuned by two gates acting respectively on the left and on the right half. The device can then be operated in the unipolar n-n' and p-p' or in the bipolar n-p' and p-n' regimes. In all these regimes we observed a striking beating pattern, which can be traced back to Fabry-Perot oscillations that are either localized in one half of the sample (left and/or right) or even extend over the whole sample with a length exceeding $1\,\mu$m. Theoretical modeling [3] has provided a lot of insight into the role of contact doping and the steepness of the potential in the inner part of the device, but also at the edge to the source and drain contacts. Taking all geometrical parameters of the experiment into account, a remarkable good correspondence between theory and measurement could be reached. The comparison also shows that transport is ballistic.

References

[1] N. Tombros, A. Veligura, J. Junesch, J.J. van den Berg, P.J. Zomer, M. Wojtaszek, I. J.V. Marun, H.T. Jonkman, B.J. van Wees, J. Appl. Phys. **199**, 093702 (2011).

[2] F. Freitag, J. Trbovic, M. Weiss, C. Schönenberger, Phys. Rev. Lett. **108**, 076602 (2012).

[3] M.H. Liu and K. Richter, Phys. Rev. Lett. **86**, 115455 (2012).

Quantum point contacts in the fractional quantum Hall regime

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Two-dimensional electron systems (2DES) at low temperatures and in strong magnetic fields show a rich spectrum of highly degenerate, incompressible ground states. Apart from the Laughlin sequence at filling factors $\nu = 1/m$ (m odd integer), other exotic states like the $\nu = 5/2$ state have been observed [1]. Many properties of these states are unknown and of high interest for current research.

We investigate transport through quantum point contacts (QPCs) in the integer and fractional quantum Hall (FQH) regime. We study the influence of the potential shape of QPCs on the formation and the energy gap of fractional states in the channel. Fig. 1a shows the transconductance of a tunable QPC on a high-mobility 2DES. Black regions correspond to integer and fractional quantum Hall states formed in the QPC or complete pinch-off. In the transition regime between different filling factors, resonances corresponding to the self-consistent formation of potential minima and maxima in the channel modulate the conductance. Finite bias measurements of these systems show a spectrum of conductance enhancement and suppression, currently not understood in detail. In the weak backscattering regime, we study the tunneling properties of the FQH states of the second Landau level. Fully quantized $\nu = 5/2$ and $\nu = 7/3$ states and pronounced reentrant integer quantum Hall states can be observed in the QPC (see Fig. 1b). Finite bias measurements allow for an investigation of the tunneling properties of these states [2].

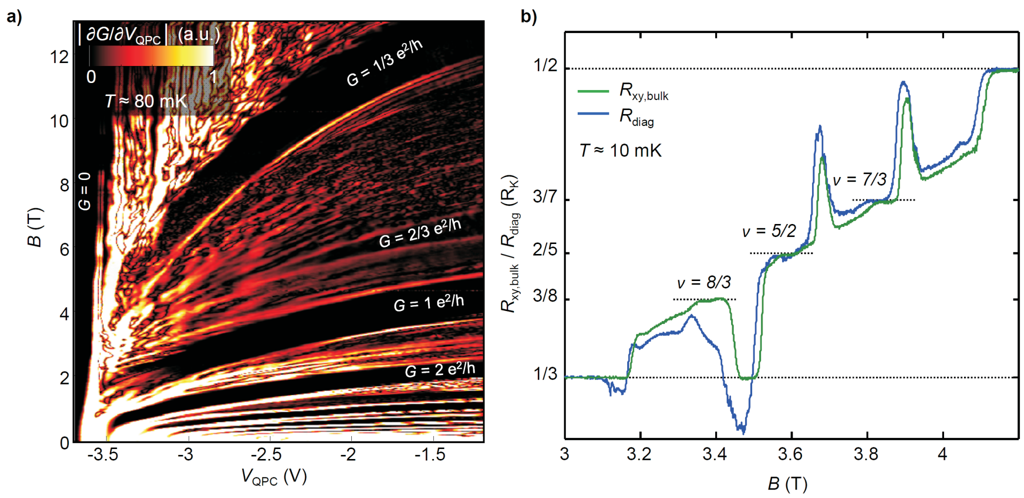

Figure 1: (a) Transconductance through a QPC as a function of the gate voltage V_{QPC} and the magnetic field B. Black regions correspond to the transmission of integer or fractional quantum Hall states through the QPC. (b) R_{diag} and $R_{xy,\text{bulk}}$ (in multiples of R_{K}) as a function of the magnetic field. The diagonal resistance across the 1.2 μm wide QPC reveals a fully quantized $\nu = 5/2$ and $\nu = 7/3$ states with weak backscattering at the QPC constriction.

References

[1] R. Willett et al., Phys. Rev. Lett. **59**, 1776 (1987).

[2] I.P. Radu et al., Science **320**, 899 (2008).

Superconductivity in $NbSe_2$ Field-Effect Transistors

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Since the first isolation of graphene in 2004 [1] interest in intrinsic superconductivity and the superconducting proximity effect in single atomic or few-layer crystals has grown rapidly [2]. Here we describe investigations of the superconducting transition in few molecular layer dichalcogenide flakes. Our lithographically-defined 4-terminal devices have been realised by micromechanical cleavage from a 2H-$NbSe_2$ single crystal onto Si/SiO_2 substrates followed by the deposition of Cr/Au contacts (c.f., the atomic force microscope (AFM) image in upper inset of Fig. 1). AFM and Raman spectroscopy have been used to characterise the quality and number of molecular layers present in our flakes [3].

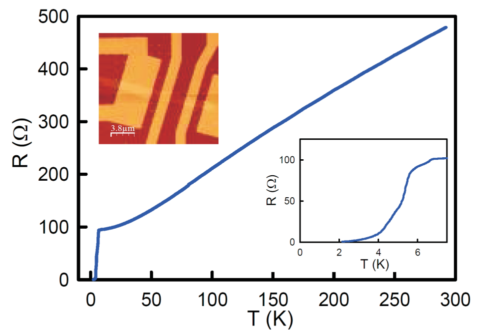

Figure 1: Temperature dependence of the 4-point resistance of a typical device. Inset: (top left) AFM scan of a completed structure; (bottom right) expanded view of the resistive superconducting transition.

While our very thinnest $NbSe_2$ flakes did not appear to conduct at low temperatures, slightly thicker flakes were superconducting with an onset T_c that is only slightly depressed from the bulk value (7.2 K). The main curve of Fig. 1 shows the 4-point resistance of a device from 0-300 K. The resistance typically shows a small, sharp high temperature transition followed by one or more broader transitions which end in a wide tail to zero resistance at low temperatures (c.f., lower inset of Fig. 1). The temperature of the highest transition drops slowly as the flake thickness decreases in agreement with earlier works [4,5]. Estimates of the 300 K resistivity for our flakes are several times higher than that found in bulk single crystals, and we speculate that these multiple resistive transitions are related to disorder in the layer stacking rather than lateral inhomogeneity as was proposed by Frindt [4]. The behaviour of several flakes has been characterised as a function of temperature, applied field and back-gate voltage. We find that the sheet resistance and transition temperatures depend weakly on the gate voltage, with both conductivity and T_c decreasing as the electron concentration is increased. The application of a perpendicular magnetic field up to 1 T leads to an approximately linear reduction in the temperature at which the resistive transitions are observed, and these data have been analysed to infer effective values of the $T = 0$ upper critical field, $H_{c2}(0)$, and Ginzburg-Landau coherence length, $\xi(0)$. Our results will be analysed in terms of available theories for these phenomena.

References

[1] Novoselov K. S., *et al.*, PNAS **102**, 10451 (2005).
[2] Heersche, H.B., *et al.*, Nature **446**, 56 (2007).
[3] Dattatray J. Late, *et al.*, Advanced Functional Materials **22**, 1894 (2012).
[4] Frindt, R. F., Physical Review Letters **28**, 299 (1972).
[5] Neal E. Staley, *et al.*, Physical Review **B 80**, 184505 (2009).

Quantum magnetooscillations in disordered graphene

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We present the results of calculations of the dynamic magnetoconductivity $\sigma(\omega)$ of disordered graphene[1] and make connections to recent experiments.[2] Analytic expressions for $\sigma(\omega)$ are obtained in various parametric regimes ranging from the quasiclassical Drude limit corresponding to strongly overlapping Landau levels (LLs) to the extreme quantum limit where the conductivity is determined by the optical selection rules of the clean graphene. The nonequidistant LL spectrum of graphene renders its transport characteristics quantitatively different from conventional 2D electron systems with parabolic spectrum. Since the magnetooscillations in the semiclassical density of states are anharmonic and are described by a quasi-continuum of cyclotron frequencies, both the ac Shubnikov-de Haas oscillations and the quantum corrections to $\sigma(\omega)$ that survive to higher temperatures manifest a slow beating on top of fast oscillations with the local energy-dependent cyclotron frequency. Correspondingly, both types of quantum oscillations possess nodes at characteristic frequencies. In the quantum regime of separated LLs, we study both the cyclotron-resonance transitions, which have a rich spectrum due to the nonequidistant spectrum of LLs, and the disorder-induced transitions violating the clean selection rules of graphene. The strongest disorder-induced transitions can be identified in recent magnetotransmission experiments. [2] We also compare the temperature- and chemical potential-dependence of $\sigma(\omega)$ in various frequency ranges: from the dc limit (allowing intra-LL transitions only) to the universal high-frequency limit (where the Landau quantization provides a small B-dependent correction to the universal value of the interband conductivity of the clean graphene). The obtained results also form a basis for future studies of nonequilibrium magnetotransport phenomena[3] in graphene driven by strong ac and dc fields.

References

[1] U. Briskot, I. A. Dmitriev, and A. D. Mirlin, arXiv:1301.7246 (2013)

[2] M. Orlita, C. Faugeras, R. Grill, A. Wysmolek, W. Strupinski, C. Berger, W. A. de Heer, G. Martinez, and M. Potemski, Phys. Rev. Lett. **107**, 216603 (2011).

[3] I.A. Dmitriev, A. D. Mirlin, D. G. Polyakov, and M. A. Zudov, Rev. Mod. Phys. **84**, 17091763 (2012).

Quantum Transport Phenomena at the MgZnO/ZnO Heterointerface

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A MgZnO/ZnO heterostructure, an outstanding emergeny oxide two-dimensional high mobility electron system (2DES) reaching a mobility of 700,000 cm2/Vs[1], exhibits electron correlation effects over the entire magnetic field range [2]. We explore this from temperature-dependent magnetotransport studies for several high-mobility heterostructures with various charge-carrier densities. In low magnetic fields the electron correlation manifests itself as a 60% enhancement of electron mass, while in high magnetic fields, our novel heterostructures exhibit a sequence of fractional quantum Hall states at $\nu = p/(2p{\pm}1)$ with p up to as high as 5 in the lowest Landau level. We analyze the activation energy of the FQH states, and apply the picture of composite fermions (CFs) around ν=1/2. The CF mass has turned out to increase linearly with the magnetic field, and thus shows a different functional field dependence than predicted by a noninteracting CF and experimentally reported for GaAs-based 2DES. A comparison of temperature dependent transport at B=0 and ν=1/2 indicates also: (1) a large residual interaction between CFs; (2) a phonon scattering more effective for CFs than for electrons.

We also present the experimental results obtained in the magnetic field up to 33 T at dilution fridge temperatures, where fractional states upto ν=1/5 are observed.

Furthermore, the electron energy ladder is mapped by tilting the sample in the magnetic field. Owing to both a large mass and large electron g-factor, multiple level crossings are observed accompanied with the appearance of resistance spikes. We analyze the level crossing and the electron g-factor dependence on the magnetic field. In the limit of the magnetic field being completely in-plane with the 2DES, the spin susceptibility is deduced to be 3.5 times enhanced compared to the bulk value and does not show a pronounced dependence on the charge carrier density in the range between $1.4{\cdot}10^{11}\text{cm}^{-2}$ and $3.0{\cdot}10^{11}\text{cm}^{-2}$.

References

[1] J. Falson, D. Maryenko, Y. Kozuka, A. Tsukazaki, and M. Kawasaki, Applied Physics Express **4**, 091101 (2011).

[2] D. Maryenko, J. Falson, Y. Kozuka, A. Tsukazaki, M. Onoda, H. Aoki, and M. Kawasaki, Phys. Rev. Lett. **108**, 186803 (2012).

Photovoltaic Infrared Photoresponse of the High-Mobility Graphene Quantum Hall System due to Cyclotron Resonance

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Charge carriers in graphene, massless Dirac fermions, form an unique sequence of the Landau levels in high magnetic fields. Thus, the cyclotron resonance in graphene is distinct from that of conventional two-dimensional electron systems based on semiconductors.

In this work, we studied photoresponse in a high-mobility graphene quantum Hall system on hexagonal boron nitride (h-BN). Mid-infrared light (λ = 10.6 μm) was irradiated to a graphene Hall-bar device ($\mu \sim$ 110,000 cm^2/Vs), fabricated using the mechanical exfoliation and transfer technique, and magnetotransport measurements were carrier out at T = 1.5 - 200 K and B = 0 -9 T.

We observed photoresponse signals induced by two independent mechanisms: the photovoltaic effect and the bolometric effect. The photoresponse signal, whose amplitude was independent of the bias current, was detected in a quantum Hall regime with the Landau-level filling factor $\nu = \pm 2$, thus indicating the photovoltaic effect due to the cyclotron resonance. The photoresponse signal, whose amplitude is proportional to the bias current, was detected in transition regions between quantum Hall plateaus, indicating the bolometric effect. The photovoltaic signal sustains up to T = 180 K, whereas the bolometric effect is strongly suppressed above T = 50 K. The polarity of the photovoltaic photoresponse was shown to be systematically reversed on reversal of the applied magnetic field direction and measurement geometry, suggesting that the photovoltage signals were generated along the quantum Hall edge channel.

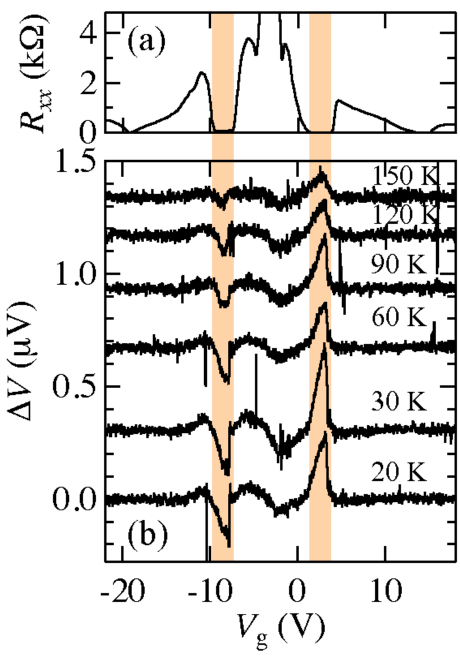

Figure 1: (a) Longitudinal resistance R_{xx} and (b) photovoltaic response ΔV as a function of back-gate bias voltage V_g measured in magnetic fields of $B = 8$ T.

Mott Variable Range Hopping and Weak Antilocalization Effect in Heteroepitaxial Na_2IrO_3 Thin Films

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Iridate thin films are a prerequisite for any application utilizing their cooperative effects resulting from the interplay of strong spin-orbit coupling and electronic correlations that are comparable in size. Here, heteroepitaxial Na_2IrO_3 thin films with excellent (001) out-of-plane crystalline orientation and well defined in-plane epitaxial relationship are presented on oxide substrates $YAlO_3$, a-Al_2O_3, c-Al_2O_3 and c-ZnO, respectively. Resistivity is dominated by a three-dimensional Mott variable range hopping mechanism in a large temperature range between 300 K and 40 K, i.e. $\rho = \rho_0 \exp[(T_0/T)^{1/4}]$. Optical experiments show the onset of a small optical gap $E_{\mathrm{go}} \approx 200$ meV and a splitting of the Ir 5d-$t_{2\mathrm{g}}$ manifold. Positive magnetoresistance below 3 T and 25 K shows signatures of a weak antilocalization effect. The corresponding magnetoconductivity is fit and analyzed quantitatively according to the Hikami-Larkin-Nagaoka equationWeak antilocalization can be associated with surface states in a topological insulator and hence supports proposals for a topological insulator phase present in Na_2IrO_3.

Bi_2Se_3 nanowires grown by molecular beam epitaxy

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Topological Insulators are the focus of immense research efforts and rapid progress is obtained in that field. Bi_2Se_3 provides a large band gap (E_G=0.3 eV) and a band structure with a single Dirac cone at the Γ-point. This makes Bi_2Se_3 one of the most promising three dimensional topological insulator materials. While Bi_2Se_3 nanowires so far were fabricated with different methods and for different purposes, we here present the first Bi_2Se_3 nanowires grown by molecular beam epitaxy. The nanowires were nucleated on pretreated, gold coated Silicon (100) wafers. Scanning electron microscope images, Figure 1, show single standing nanowires, over a covered surface. The complete wafer is covered with Bi_2Se_3 flakes with no recognizable orientation. But nanowires only nucleate in absolute proximity to scratches brought to the wafer with metal tweezers directly before mounting in the vacuum chamber. Scanning electron microscope images, transmission electron images as well as electron dispersive X-ray measurements show thin, crystalline Bi_2Se_3 nanowires. Therefore, these Bi_2Se_3 nanowires have great promise for spintronic devices and Majorana fermion observation in contact to superconductor materials. Once completely understood molecular beam epitaxy enables the control over nanowire density and shape and offers the possibility for implementation of further materials in the crystal (e.g. $Cu_xBi_2Se_3$).

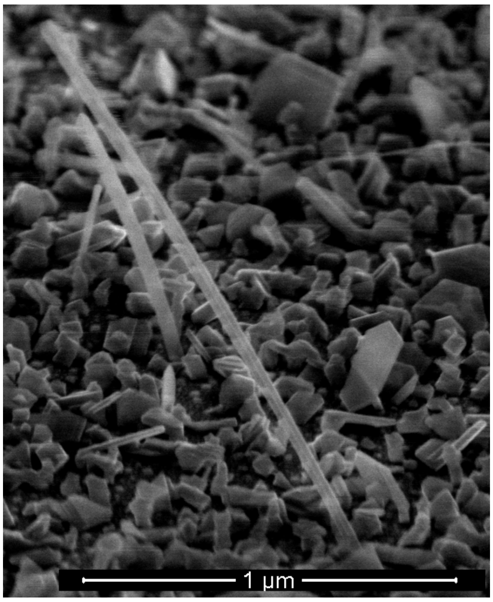

Figure 1: Single standing nanowire growing out of the surface, covered by Bi_2Se_3 flakes.

Imaging magnetoelectric subbands in ballistic constrictions

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We have measured local transport through a stadium formed by two ballistic constrictions. The conductance through the stadium is measured at 300 mK as a function of the position of a biased metallic tip of an atomic force microscope which is scanned across the sample [1, 2]. We have observed a set of unexpected fringe patterns at the constrictions (Fig. 1a) and imaged the transition from electrostatic to magnetic depopulation of subbands in one of the constrictions in a perpendicular magnetic field. We interpret the fringes as a standing wave pattern between the AFM tip and the top gates leading to quantized conductance plateaus. The fringes form a checkerboard pattern (Fig. 1b), which precisely allows determining the number of transmitted modes in each of the tip-gate constrictions.

In the quantum Hall regime moving the tip inside the constriction brings edge channels closer together, which are backscattered one by one. This is seen in spatially resolved images as wide conductance plateaus, each of which corresponds to its own local filling factor. Classical and quantum simulations describe well most of our observations.

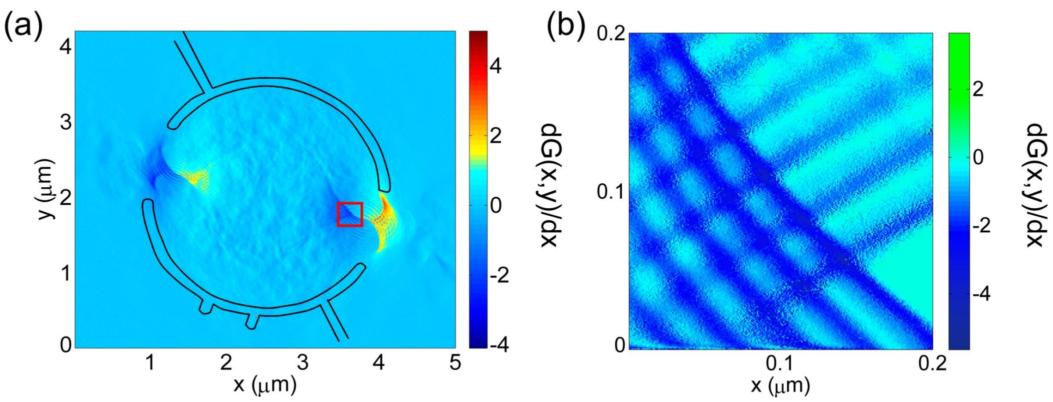

Figure 1: (a) Numerical derivative of the conductance through the stadium, dG(x, y)/dx, with respect to the x-axis as a function of tip position, (x, y). The position of the stadium is shown by black solid lines (top gates). (b) A zoom-in of the part (a red square in (a)) of right fringe pattern. The mentioned checker board pattern is clearly seen.

References

[1] M. A. Topinka *et al.*, Science **289**, 2323 (2000).

[2] A. A. Kozikov *et al.*, New J. Phys. **15**, 013056 (2013).

Shot noise thermometry of quantum Hall edge states

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We use the non-equilibrium bosonization technique to investigate effects of the Coulomb interaction on quantum Hall edge states at filing factor $\nu = 2$, partitioned by a quantum point contact (QPC). We find, that due to the integrability of charge dynamics, edge states evolve to a non-equilibrium stationary state with a number of specific features. In particular, the noise temperature Θ of a weak backscattering current between edge channels is linear in voltage bias applied at the QPC, independently of the interaction strength. In addition, it is a non-analytical function of the QPC transparency T and scales as $\Theta \propto T \ln(1/T)$ at $T \ll 1$. Our predictions are confirmed by exact numerical calculations.

Even denominator fractional quantum Hall states in ZnO

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The ZnO two-dimensional electron system (2DES) has recently emerged as an alternative platform for investigating 2D correlation physics. Advances in growth techniques now allow the realisation of samples with electron mobilities exceeding μ = 700,000 cm^2/Vs [1]. In this work, low temperature ($T \approx$ 20mK) magnetotransport is presented for a high mobility sample with a focus on half-integer filling factors.

Figure 1 displays the base temperature magnetotransport as a function of partial filling factor (ν^*) for $\nu = 7/2$ (3 + 1/2) (top) and 5/2 (2 + 1/2) (middle) at zero tilt angle, and 3/2 (1 + 1/2) (bottom) when the sample is tilted to an angle of $\theta = 40.34°$ relative to the magnetic field direction. At zero tilt, the observation of a well developed fractional quantum Hall state (FQHS) at $\nu = 7/2$ signifies the first observation of an even denominator FQHS outside of the GaAs 2DES. However, the ν = 5/2 FQHS is curiously absent. Rather, the region is asymmetric, with FQHS of ν = 8/3, 13/5 and 18/7 for $\nu^* > 1/2$ contrasted by a complete absence for $\nu^* < 1/2$. Furthermore, with rotation of the sample to $\theta \approx 40°$, a zero resistance FQHS at $\nu = 3/2$ is induced, and is quantised for only a fine tilt range of $\theta \approx 40° \pm 2°$.

Such results illustrate the high purity of state-of-the-art ZnO heterostructures and their ability to enable the exploration of new and unique facets of low dimensional electron correlation physics.

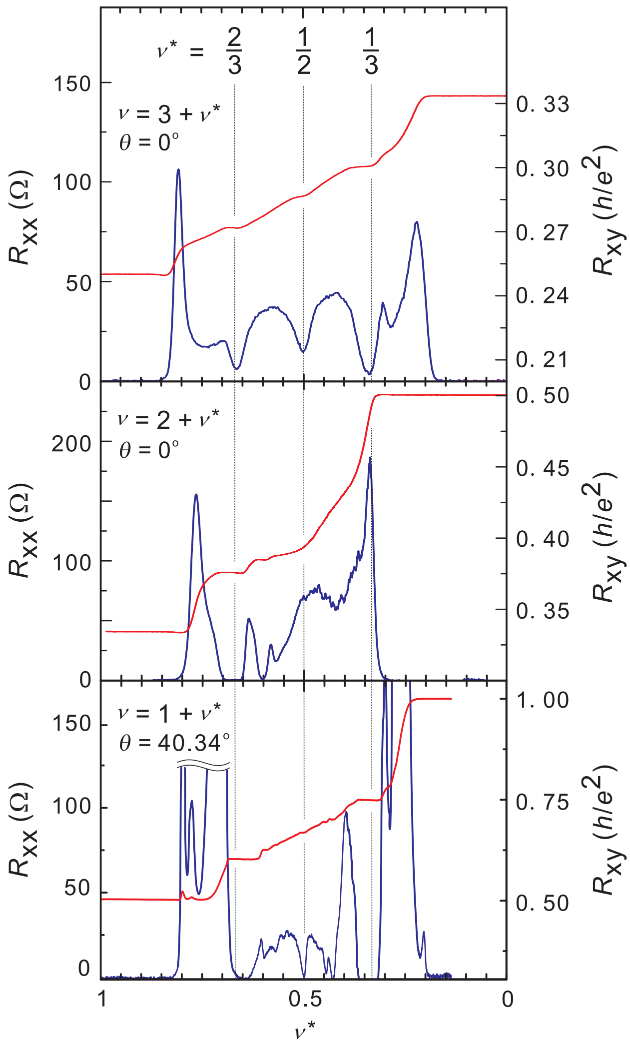

Figure 1: Base temperature magnetotransport as a function of partial filling factor (ν^*) around half-integer filling factors $\nu = 7/2$ (top), 5/2 (middle) and 3/2 (bottom).

References

[1] J. Falson, *et al.*, Appl. Phys. Express **4**, 091101 (2011).

Hanbury Brown and Twiss Interference of Anyons

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We present a study of a Hanbury Brown and Twiss (HBT) interferometer (see Fig. 1) formed with edge channels of a quantum Hall system [1]. Such a device, operating both in the integer and fractional quantum Hall regimes, can directly probe entanglement and fractional statistics of initially uncorrelated particles. Focusing on fractional filling factors, we calculate the HBT cross-correlations of Abelian Laughlin anyons. In the case of electronic tunneling between the edges, we find that the current-current correlations show an anti-bunching behavior. For quasiparticle tunneling, the correlations exhibit partial bunching similar to bosons, indicating a substantial statistical transmutation from the underlying electronic degrees of freedom. We also find qualitative differences between the anyonic signal and the corresponding bosonic or fermionic signals, showing that anyons cannot be simply thought of as intermediate between bosons and fermions.

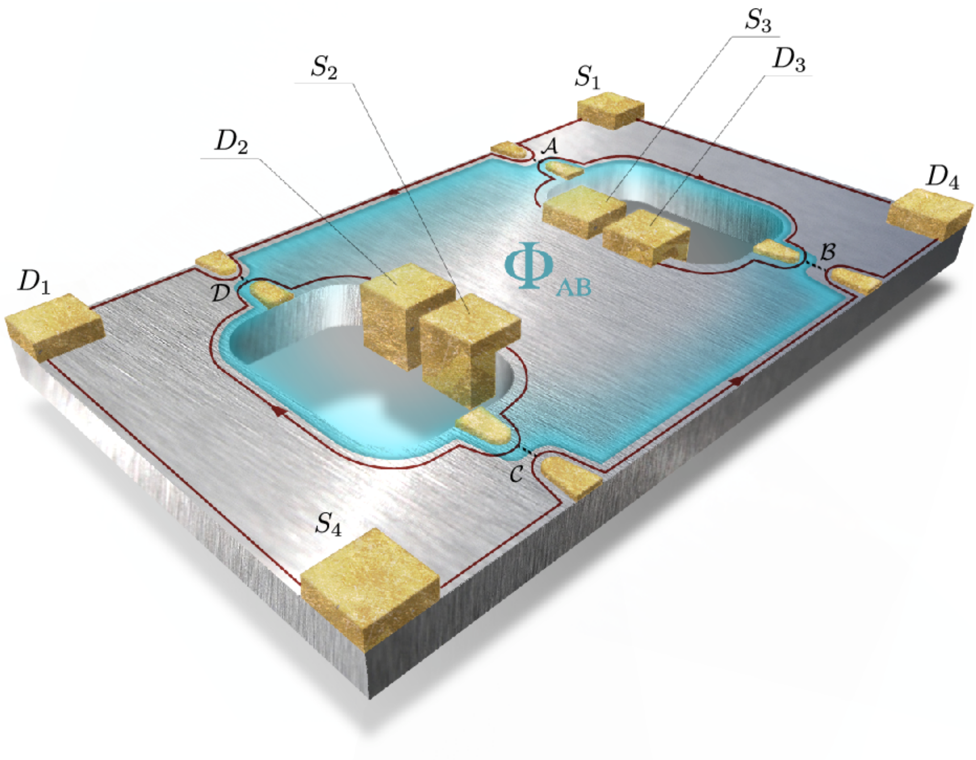

Figure 1: Hanbury Brown and Twiss interferometer based on the quantum Hall edge states.

References

[1] G. Campagnano, O. Zilberberg, I.V. Gornyi, D.E. Feldman, A.C. Potter, and Y. Gefen, Phys. Rev. Lett. **109**, 106802 (2012).

Inter-surface interaction via phonon in three-dimensional topological insulator

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We theoretically study the effects of phonon in the inter-surface electron-electron interactions on the two surfaces ξ and η of a three-dimensional topological insulator [1]. The three-dimensional topological insulator has two-dimensional massless electric states on its surface. Theoretically, without the interactions, a mass term dose not appear unless the system looses time reversal symmetry.

On the other hand, with the interactions, there is a well known dynamical mass generation for the massless fermion in association with the spontaneously symmetry breaking of chiral $U(1)$ symmetry. The dynamical mass appear when two Dirac cones are coupled attractively. Therefore, it is important to make the conditions clear in which the inter-surface electron-electron interaction is attractive. The phonon excitation in the bulk plays an important role in mediating the inter-surface electron-electron interactions because the Coulomb interaction is suppressed in TIs with a much larger dielectric constant than that in the vacuum.

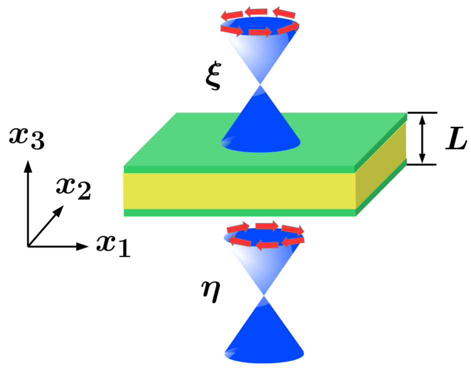

Figure 1: Two surface states in three-dimensional topological insulator are shown. There is a single massless Dirac particle on a single surface of the topological insulator.

In this work, we first derive the effective Lagrangian describing the two surface states with the interaction between them from a model of three dimensional topological insulator including the phonon excitation in it. The inter-surface electron-electron interaction can be either repulsive or attractive depending on parameters such as temperature, the speed of phonon, and the Fermi velocity of the surface states. The attractive interaction removes the Dirac nodes at the two surface states in association with the spontaneously symmetry breaking. On the basis of the calculated results, we also discuss how to tune the inter-surface interaction.

References

[1] T. Habe, arXiv:1304.5012.

Effects of pseudophonons in suspended graphene on Dirac fermion transport

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When a graphene sheet is clamped at two parallel leads as illustrated in Fig. 1(a), the deformation of the sheet is induced by applying an electric field which can influence on quantum transport [1]. In this study, we show that a time-periodic strain of the suspended graphene produces inelastic scattering of electrons as a consequence of an interaction between electrons and pseudophonons.

We consider the effective vector potential induced by the time-periodic strain is given as

$$\vec{A}(\vec{r},t) = \frac{\beta h_0^2}{6a_0 L^2}\left[\theta\left(x+\frac{L}{2}\right) - \theta\left(x-\frac{L}{2}\right)\right]\cos\omega t, \tag{1}$$

where $\beta = C\left(\partial \ln t/\partial \ln a_0\right) \approx 2$ with $C \sim 1$, $t \approx 3\ eV$, $a_0 \approx 1.4\mathring{A}$, h_0 is the vertical deformation, L is the length of the suspended region, and ω is the frequency of the time-periodic strain. By using Floquet scattering theory, eigenstates of the system is given as

$$\Psi(\vec{r},t) = e^{ik_y y}\sum_{n,m=-\infty}^{+\infty} c_m e^{ik_x^m x} J_{n-m}(\chi)\, e^{-i(E-n\hbar\omega)t}, \tag{2}$$

where $k_x^m = \sqrt{\left[(E+m\hbar\omega)/(\hbar v_F)\right]^2 - \left[k_y + (n\omega)/(v_F\Lambda)\right]^2}$ with $\Lambda = \psi^\dagger\sigma_y\psi$ and $J_{n-m}(\chi)$ is the Bessel function of the first kind with $\chi = \left[(ev_F\beta\Lambda)/(6a_0\hbar\omega)\right](h_0/L)^2$. Electrons can be scattered from pseudophonons by gaining or losing both energy and momentum quanta; $n\hbar\omega$ and $(n\hbar\omega)/(v_F\Lambda)$, as shown in Fig. 1(b). The strength of the electron-pseudophonon scattering is determined by $J_{n-m}(\chi)$.

Our main finding in this study is that the electron-pseudophonon interaction depends on the incident angle of electron since $J_{n-m}(\chi)$ has the angle-dependence. The angle-dependent feature of the electron-pseudophonon interaction allows normally incident electrons to propagate through suspended region without any inelastic scattering despite of the existence of the strain.

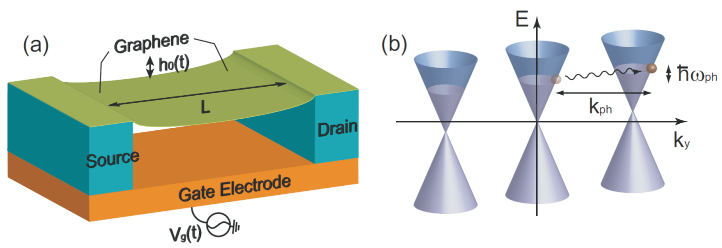

Figure 1: (a) Schematic view of the system. (b) Graphitic diagram of inelastic scattering as a result of the electron-pseudophonon interaction.

References

[1] M. M. Fogler, F. Guinea, M. I. Katsnelson, Phys. Rev. Lett. **101**, 226804 (2008).

Tilted magnetic field dependent measurements in a high mobility two-dimensional electron gas

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We study the fractional Quantum-Hall effect in a high mobility two-dimensional electron gas (2DEG). Hall geometries are created by photolithography on a GaAs/AlGaAs quantum well containing a 2DEG. The 2DEG has an electron density of $n_e = 3.3 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and a mobility of $\mu_e = 11.9 \cdot 10^6\,\mathrm{cm}^2/\mathrm{Vs}$.

Tilted magnetic field dependent measurements have been carried out in the range of the fractional filling factor $\nu = 5/2$ and $\nu = 7/2$. Not only the previous reported enhancement of the filling factor $\nu = 5/2$ for small tilt angles Θ is observed but also a similar behaviour for the filling factor $\nu = 7/2$ (see Figure 1) [1]. For $\Theta = 0°$ no minimum is detected in the longitudinal resistivity ρ_{xx} at the position of the filling factor $\nu = 7/2$ but the depth of the minimum increases by increasing the angle till $\Theta = 26°$. Also the activation energy of the filling factor $\nu = 11/3$ increases for higher tilt angle Θ. Above $\Theta = 60°$ the minima vanishes in this magnetic field range. We assume that the effect of the Re-entrant integer Quantum-Hall dominates this regime that is why the fractional filling factor disappears for higher tilt angles.

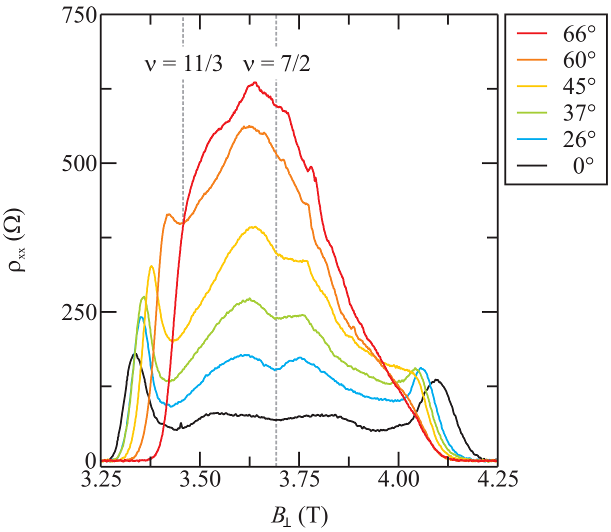

Figure 1: The longitudinal resistivity ρ_{xx} vs. the magnetic field B for different angles. The filling factor $\nu = 7/2$ showes a slight increse for small tilt angles leading to assumption of a similar behaviour as the filling factor $\nu = 5/2$ [1].

References

[1] G. Liu, C. Zhang, D. C. Tsui, I. Knez, A. Levine, R. R. Du, L. N. Pfeiffer and K. W. West Phys. Rev. Lett. **108**, 196805 (2012).

Fermion-parity anomaly of the critical supercurrent in the quantum spin-Hall effect

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The helical edge state of a quantum spin-Hall insulator can carry a supercurrent in equilibrium between two superconducting electrodes (separation L, coherence length ξ). We calculate the maximum (critical) current I_c that can flow without dissipation along a single edge, going beyond the short-junction restriction $L \ll \xi$ of earlier work, and find a dependence on the fermion parity of the ground state when L becomes larger than ξ. Fermion-parity conservation doubles the critical current in the low-temperature, long-junction limit, while for a short junction I_c is the same with or without parity constraints. This provides a phase-insensitive, DC signature of the 4π-periodic Josephson effect.

Nanoscale magnetism and electronic phase separation at LAO/STO interfaces

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Ferromagnetism and superconductivity are in most cases adverse. However, recent experiments reveal that they coexist at interfaces of $SrTiO_3$ and $LaAlO_3$ (LAO/STO) [1, 2]. Using a combination of density functional and field theoretical methods, we analyze the magnetic state of the LAO/STO and provide evidence that it is caused by the spin polarization of Ti 3d interface electrons and depends strongly on the oxidation state of the interfaces [3, 4]. We show that oxygen vacancies induce a complex multiorbital reconstruction which involves a lowering of the local symmetry and an inversion of t_{2g} and e_g orbitals resulting in the occupation of the eg orbitals of Ti atoms neighboring the O vacancy. In contrast to stoichiometric nonmagnetic LAO/STO, the vacancy-induced orbital reconstruction generates a two-dimensional interface magnetic state not observed in bulk $SrTiO_3$. This allows for the notion that areas with increased density of oxygen vacancies produce ferromagnetic puddles and account for the previous observation of a superparamagnetic behavior in the superconducting state. We analyze the electronic phase separation and investigate effective double-exchange coupling of the two-dimensional spin-polarized electron liquid at titanate interfaces. We also discuss novel mechanism of ferromagnetic interactions between local triplet states of Ti ions induced by random oxygen defects.

References

[1] Lu Li, C. Richter, J. Mannhart, and R.C. Ashoori, Nature Physics, **7**, 762 (2011).

[2] J. A. Bert, B. Kalisky, C. Bell, M. Kim, Y. Hikita, H.Y. Hwang, K.A. Moler, Nature Physics **7**, 767 (2011).

[3] N. Pavlenko, T. Kopp, E.Y. Tsymbal, G.A. Sawatzky, and J. Mannhart, Phys. Rev. B **85**, 020407(R) (2012).

[4] N. Pavlenko, T. Kopp, E.Y. Tsymbal, J. Mannhart, and G.A. Sawatzky, Phys. Rev. B **86**, 064431 (2012).

Magneto-transport in MoS_2: Phase Coherence, Spin Orbit Scattering and the Hall Factor

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We have characterized phase coherence length, spin orbit scattering length, and the Hall factor in n-type MoS_2 2D crystals via weak localization measurements and Hall-effect measurements. Weak localization measurements reveal a phase coherence length of 50 nm at $T = 400$ mK, decreasing as $T^{-1/2}$ with increased temperatures. Weak localization measurements also allow us, for the first time without optical techniques, to estimate the spin orbit scattering length to be 500 nm, pointing to the potential of MoS_2 for spintronics applications. Via Hall-effect measurements, we observe a low temperature Hall mobility of 311 cm^2/Vs at $T = 1$ K which decreases as a power law with a characteristic exponent $\gamma = 1.5$ from 10 K to 60 K. At room temperature, we observe Hall mobility of 24 cm^2/Vs. By determining the Hall factor for MoS_2 to be 1.35 at $T = 1$ K and 2.4 at room temperature, we observe drift mobility of 420 cm^2/Vs and 56 cm^2/Vs at $T = 1$ K and room temperature, respectively.

Emergence of domains and nonlinear transport in the zero-resistance state

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I will discuss transport in the domain state, the so-called zero-resistance state, that emerges in a two-dimensional electron system in which the combined action of magnetic field and microwave radiation produces a negative absolute conductivity and results in an electrical instability. This state was discovered in ultra high-mobility 2D electron systems in semiconductor heterostructures and, more recently, in 2D electron systems on the surface of liquid helium. It will be shown that the voltage-biased system has a rich phase diagram depending on the system size and bias voltage, with second- and first-order nonequilibrium phase transitions between the domain and homogeneous states for small and large voltages, respectively. Particular attention will be paid to the residual negative dissipative resistance in the stable domain state. The phase transitions manifest themselves in the current-voltage characteristic as kinks (second order) or jumps in the current (first order).

Influence of Edges on Quantum Hall Potential Profiles in Graphene

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In the case of a two-dimensional electron system (2DES) in a GaAs/(Al,Ga)As heterostructure, the electronically compressible and incompressible landscape within the 2DES determines the Hall potential profile and current distribution under quantum Hall conditions: The Hall potential drops as well as the dissipationless current can be found within incompressible regions which evolve with increasing magnetic field from the depletion regions along the 2DES edges towards the 2DES bulk [1].

We were able to extract Hall potential profiles on a graphene flake, deposited on a SiO_2/Si substrate, using a scanning probe technique [2] at 1.4 Kelvin under QHE conditions. For n-type graphene (see Fig. 1 above 3 V in backgate voltage), we found a similar evolution of Hall potential profiles as for quantum Hall samples from GaAs/(Al,Ga)As heterostructures: Measuring the Hall potential profile at fixed magnetic field at the higher filling factor plateau side one finds first two pronounced Hall potential drops at the edges. When decreasing the mean electron density by the backgate voltage (= lowering the bulk filling factor for electrons), these drops get wider and move closer towards the bulk, and finally merge and extend over the bulk. The position shift of the pronounced Hall voltage drops versus back gate voltage leads to the u-shape like feature visible in the color plot of Fig. 1. These results show that - as in the case of a 2DES in a GaAs/(Al,Ga)As heterostructure - in graphene there exists an extended electrostatic depletion region along the 2DES edges in the order of 1 μm.

In the case of p-type graphene (see Fig. 1 below 3 V backgate voltage), the polarity of the Hall voltage is - as expected - reversed. We also find a characteristic evolution of the Hall potential profile with decreasing back gate voltage, however the position of pronounced Hall voltage drop move from the edges towards the bulk with increasing charge carrier (= hole) concentration, i.e., with increasing filling factor. We have to conclude that there exists a hole accumulation towards the edges of the p-type regime of the graphene flake. This can be well understood if fixed negative charges are positioned besides the graphene flake on the SiO_2 surface.

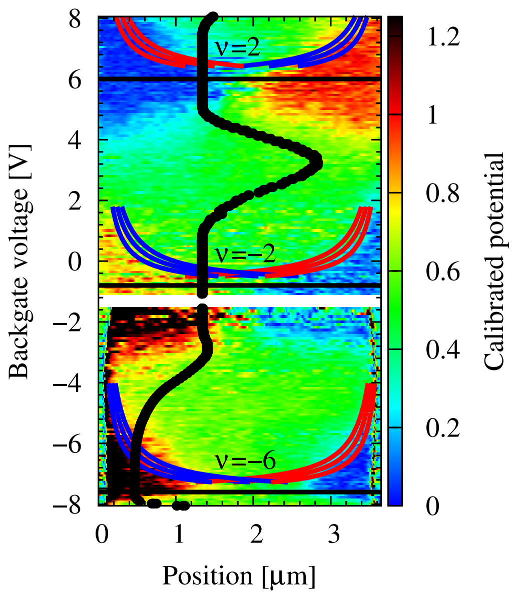

Figure 1: Color-coded Hall potential profiles across a 3.6 μm wide graphene flake as a function of the backgate voltage. The profiles were calibrated with respect to the applied bias voltage. The red and blue lines are the fitted positions of incompressible strips. The fitted positions for the bulk filling factors $\nu = 2$, -2 and -6 are marked with black lines.

References

[1] Review: J. Weis and K. v. Klitzing, Phil. Trans. R. Soc. **A 369**, 3954-3974 (2011).

[2] P. Weitz, E. Ahlswede, J. Weis, K. v. Klitzing, K. Eberl, Appl. Surf. Sci. **157**, 349 (2000)
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Hall Potential Profile and Current Distribution towards Quantum Hall Effect Breakdown

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The dominant limitation for the accuracy of a quantum Hall resistance standard is the onset of dissipation beyond a critical current through the quantum Hall sample. This onset is referred to as the electrical breakdown of the quantum Hall effect (QHE) [1]. Several mechanisms like electron heating [1, 2], inter- [3] and intra- [4] Landau level scattering have been proposed to explain the breakdown.

Measuring the Hall potential profiles by a scanning probe technique [5, 6] gives direct insight into the current distribution in quantum Hall samples. Former measurements have revealed the important role of compressible and incompressible strips present in the depletion region along the edges of the two-dimensional system for current distribution in the quantum Hall regime [7]-[11]: On the QHE plateau side of bulk filling factor $\nu > i$, the innermost incompressible strip along both edges of the sample carries the biased current dissipationless, whereas in the QHE plateau region with $\nu \approx i$ the bulk disorder/inhomogeneity dominates and the current flows widely distributed in the incompressible bulk regions, passing compressible droplets.

Consistent with these results, we observe on the sample sketched in Fig. 1c different behavior of the QHE breakdown above and below $\nu = 2$ in the current vs. longitudinal voltage characteristics as well as in the Hall profiles with increasing Hall voltage. For $\nu > 2$, the Hall potential profile shows pronounced drops of the Hall voltage at both edges which become more and more asymmetric with increasing Hall voltage (Fig. 1a). We attribute this to the width change of incompressible strips with increasing Hall voltage [12]. For $\nu \approx 2$, where disorder dominates, the changes happen almost abruptly with increasing Hall voltage (Fig. 1b).

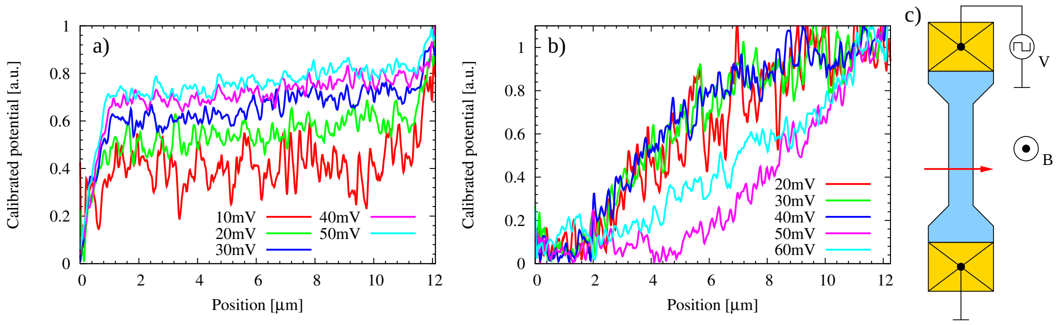

Figure 1: Measured Hall potential profiles for the filling factors (a) $\nu = 2.14$ and (b) $\nu = 1.97$. (c) Sample geometry with 10 μm width in the middle. The red arrow marks the scan line.

References

[1] G. Ebert, K. v. Klitzing, K. Ploog and G. Weimann, J. Phys. **C 16**, 5441 (1983).
[2] S. Komiyama, T. Takamasu, S. Hiyamizu, S. Sasa, Solid State Commun. **54**, 479 (1985).
[3] L. Eaves and F. W. Sheard, Semicond. Sci. Technol. **1**, 346 (1986).
[4] P. Středa and K. v. Klitzing, J. Phys. **C 17**, L483 (1984).
[5] K. McCormick, M. Woodside, M. Huang, M. Wu, P. McEuen, C. Duruoz, J. Harris, Phys. Rev. **B 59**, 4654 (1999).
[6] P. Weitz, E. Ahlswede, J. Weis, K. v. Klitzing, K. Eberl, Appl. Surf. Sci. **157**, 349 (2000).
[7] P. Weitz, E. Ahlswede, J. Weis, K. v. Klitzing, K. Eberl, Physica **E 6**, 247 (2000).
[8] E. Ahlswede, P. Weitz, J. Weis, K. v. Klitzing, K. Eberl, Physica **B 298**, 562 (2001).
[9] E. Ahlswede, J. Weis, K. v. Klitzing and K. Eberl, Physica **E 12**, 165 (2002).
[10] F. Dahlem E. Ahlswede, J. Weis and K. v. Klitzing, Phys. Rev. **B 82**, 121305(R) (2010).
[11] J. Weis and K. v. Klitzing, Phil. Trans. R. Soc. **A 369**, 3954-3974 (2011).
[12] R.R. Gerhardts, K. Panos, and J. Weis, accepted by New J. Phys. (2013).

Ballistic electron transfer between quantum dots

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We investigate non equilibrium electron transfer between two spatially separated quantum dots (QDs). Our efforts aim at realizing a weak-measurement protocol in a solid-state environment, as introduced by Aharonov *et al.* [1] in 1988. In contrast to a strong von Neumann measurement, a weak measurement couples the investigated system weakly to the measuring device. In a second step a strong von-Neumann measurement is performed to post-select the system. The introduced concept has since been successfully applied in optical experiments (e.g. [2, 3]) and the physical meaning of such obtained weak values are the subject of current debate.

Our system of choice is a top-gated GaAs/AlGaAs heterostructure. The sample consists of two QDs separated by 2 μm, as shown in the scanning electron micrograph in figure 1. The QDs can be tuned individually for selective energy emission or detection of "hot" non equilibrium electrons. An illustration of ballistic electron transport is shown in figure 2(a) with the corresponding experimental finding shown in figure 2(b). The energy level of the detector QD is set $\Delta E \approx 200\ \mu eV$ above the reservoire's Fermi level. Now source and emitter energy are simultaneously increased, while the current through the detector dot is recorded. The peak around $V_{\mathrm{emitter}} = -200\ \mu$V (red) corresponds to ballistic transfer of electrons. The blue region at higher energies corresponds to electrons which lost energy on the way between the two QDs. Future studies will aim at performing a weak measurement in the emitter QD, followed by a post-selection process in the second QD.

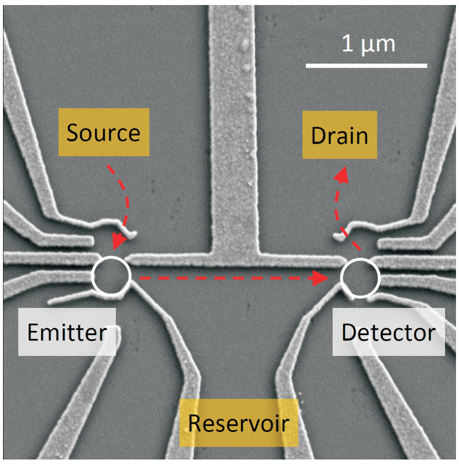

Figure 1: Scanning electron micrograph of the sample. The GaAs surface appears dark, the underlying two-dimensional electron system provides source, drain and reservoir. Negatively biased Schottky top gates (bright stripes) define two quantum dots (white circles).

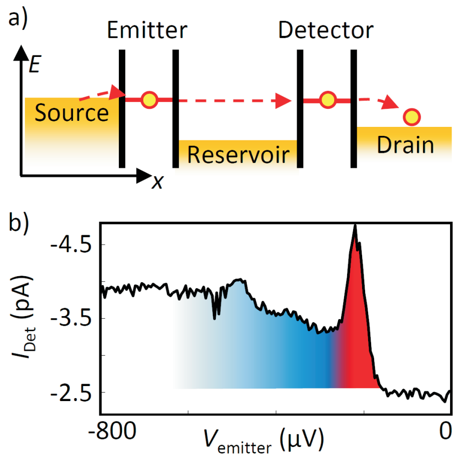

Figure 2: (a) Energy scheme describing ballistic transport between emitter QD and detector QD. (b) Detector current as a function of emitter voltage. A pronounced ballistic peak (red) and a region of energy relaxed electrons (blue) is observed.

References

[1] Y. Aharonov, D. Z. Albert, and L. Vaidman, Phys. Rev. Lett. **60**, 1351 (1988).
[2] N. W. M. Ritchie, J. G. Story, and R. G. Hulet, Phys. Rev. Lett. **66**, 1107 (1991).
[3] O. Hosten and P. Kwiat, Science **319**, 787 (2008).

Ambipolar high-mobility transistors in undoped GaAs/AlGaAs quantum wells

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In an ambipolar device, electrons or holes can be populated on demand in the same conduction channel, with their different properties such as effective mass and spin-orbit coupling. In GaAs/AlGaAs heterostructures, standard modulation doped techniques cannot easily be used as the dopant determines the polarity of the carriers and precludes the formation of the other carrier type. Undoped heterostructures, where the two-dimensional (2D) gas is formed entirely by field effect [1], allow either electrons or holes to populate the channel dependent upon the polarity of the gate voltage, if both n-type and p-type ohmic contacts exist [2]. Unlike in graphene or in carbon nanotubes, there is a 1.5V voltage window between either electron or hole population, (primarily determined by the bandgap of GaAs, 1.52eV).

We have fabricated undoped ambipolar GaAs-based quantum well devices, with different well widths (L=10-25nm) with patterned Ti/Au back and front gates, using a flip-chip process [4, 5]. This method allows a large range of densities to be achieved, *e.g.* from $7\times10^9\,\mathrm{cm}^{-2}$ to $5\times10^{11}\,\mathrm{cm}^{-2}$ in a single device with single subband occupation, and without any parallel conduction of any kind. It also enables us to precisely control the wavefunction's position in the quantum well over a wide range, which we characterise by the variable α (Figure 1).

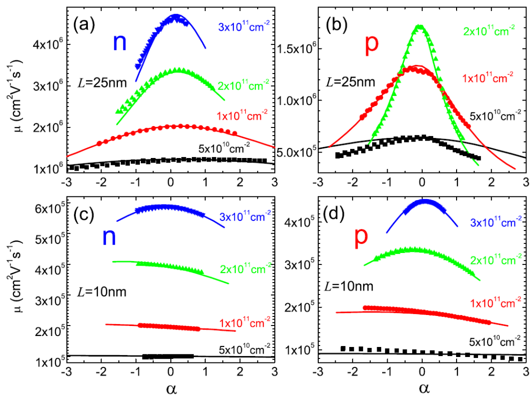

Figure 1: Electron/hole mobilities versus α for L=10nm and 25nm, where $\alpha = (\vec{E}_{front} - \vec{E}_{back})/|(\vec{E}_{front} + \vec{E}_{back})|$.

The change with α of the mobility (points in Figure 1) can be attributed to the relative change of interface roughness scattering from the two interfaces. We have modelled the mobility (solid lines in Figure 1) in the zero temperature limit within the Boltzmann transport formalism [3, 6], with numerically-solved wavefunctions, allowing us to independently characterise the two interfaces. As a growth optimisation tool, the information thus gained on the various scattering mechanisms present will help the development of very high mobility structures.

In conclusion, we have shown an excellent platform for creating high mobility two-dimensional electron gases ($4.7\times10^6\,\mathrm{cm}^2V^{-1}s^{-1}$ at n=$2\times10^{11}\,/\mathrm{cm}^2$) and hole gases ($1.8\times10^6\,\mathrm{cm}^2V^{-1}s^{-1}$ at p=$2\times10^{11}\,/\mathrm{cm}^2$), with considerable tunability which may assist the study of fractional quantum Hall states.

References

[1] B.E. Kane *et al.*, Appl. Phys. Lett. **63**, 2132 (1993).
[2] J.C.H. Chen *et al.*, Appl. Phys. Lett. **100**, 052101 (2012).
[3] A.F. Croxall *et al.*, Appl. Phys. Lett. **102**, 082105 (2013).
[4] K.D. Gupta *et al.*, Semicond. Sci. Technol. **27**, 115006 (2012).
[5] M.V. Weckwerth *et al.*, Superlattices Microstruct. **20**, 561 (1996).
[6] W.Y. Mak *et al.*, Appl. Phys. Lett. **97**, 242107 (2010).

Magnetotransport along a boundary: From coherent electron focusing to edge channel transport

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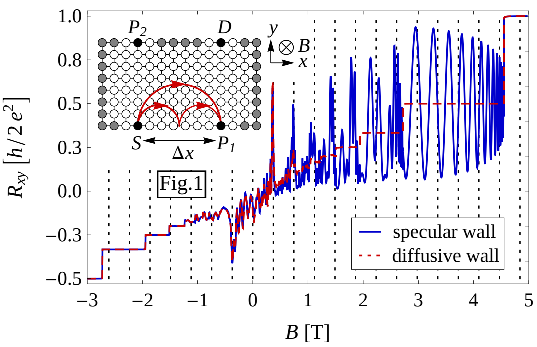
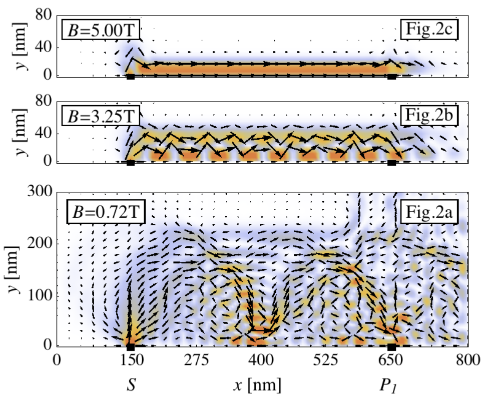
We study theoretically how electrons, coherently injected at one point on the boundary of a two-dimensional electron system, are focused by a perpendicular magnetic field B onto another point on the boundary, see the inset of Fig. 1. Using the non-equilibrium Green's function approach, we calculate the generalized 4-point Hall resistance $R_{xy} = (U_{P_1} - U_{P_2})/I_{SD}$ as a function of B.

In weak fields, R_{xy} (solid curve in Fig. 1) shows the characteristic equidistant peaks, which are observed in the experiment and which can be explained by classical cyclotron orbits speculary reflected at the boundary. These classical trajectories can be clearly seen in the local current and the local DOS of the injected electrons (Fig. 2a). In strong fields, the Hall resistance shows a single extended plateau $R_{xy} = h/2e^2$ reflecting the quantum Hall effect. The current is carried by a single edge channel straight along the boundary (Fig. 2c).

In intermediate fields, instead of lower Hall plateaus as in the case of a diffusive boundary (dashed curve in Fig. 1), we find [1] *anomalous oscillations*, which are neither periodic in $1/B$ (quantum Hall effect) nor periodic in B (classical cyclotron motion). These oscillations can be explained by the interference of the occupied edge channels causing beatings in R_{xy}. The Fig. 2b shows this interference between two occupied edge channels, which resembles also to some extent a cyclotron motion. Moreover, in this regime of two occupied edge channels, the beatings constitute a new commensurability between the magnetic flux enclosed within the edge channels and the flux quantum h/e. Introducing decoherence and a partially diffusive boundary shows that this new effect is quite robust.





References

[1] T. Stegmann, D. E. Wolf, A. Lorke, arXiv:1302.6178, submitted to Phys. Rev. B

Majorana fermions from Landau quantization in a superconductor–topological-insulator hybrid structure

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We show that the interplay of cyclotron motion and Andreev reflection experienced by massless Dirac-like charge carriers in topological-insulator surface states generates a Majorana-particle excitation [1]. Based on an envelope-function description of the Dirac-Andreev edge states, we discuss the kinematic properties of the Majorana mode and find them to be possible to be tuned by changing the superconductors chemical potential and/or the magnitude of the perpendicular magnetic field. Our proposal opens up new possibilities for studying Majorana fermions in a controllable setup. Besides avoiding materials-science challenges associated with fabrication of hybrid structures involving three different kinds of materials [2, 3], our setup also offers several new features enabling the manipulation of the Majorana excitations properties. Furthermore, a ferromagnetic insulator is not required in our realization (see Fig. 1).

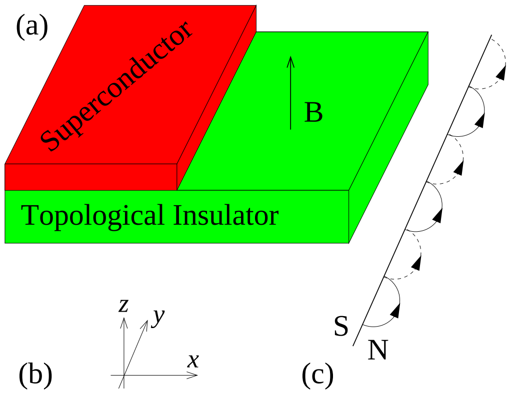

Figure 1: (Color online) (a) Schematics of the proposed sample layout. (b) The coordinate system. (c) The semiclassical picture of Dirac-Andreev edge states (solid and dashed lines represent electrons and holes respectively).

References

[1] R. P. Tiwari, U. Zülicke, and C. Bruder, Phys. Rev. Lett. (in press) arXiv:1210.4057.
[2] L. Fu and C. L. Kane, Phys. Rev. Lett. **100**, 096407 (2008).
[3] L. Fu and C. L. Kane, Phys. Rev. Lett. **102**, 216403 (2009).

Where are the electrons flowing? Self-consistent transport and boundary conditions in finite quantum Hall devices.

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The theoretical result for the current-density distribution in Hall devices depends critically on the choice of boundary conditions at the source (injection hot spot) and drain contacts. In the classical limit I show results from the (to my knowledge) first microscopic ab initio calculation [1] of the Hall potential of 10,000 interacting electrons, resulting in the potential shown in Fig. 1.

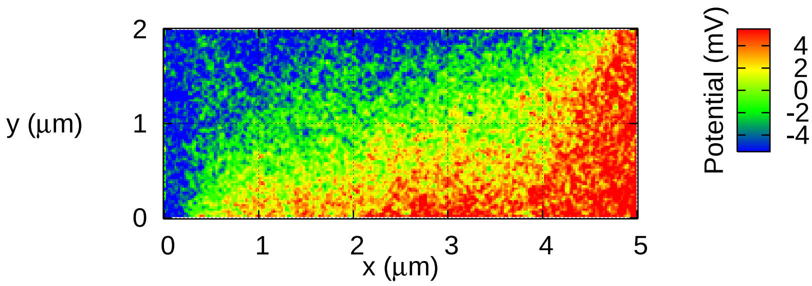

Fig. 1: Theoretical many-electron (10,000 Coulomb interacting electrons) computation of the classical Hall potential in a GaAs semiconductor device. The form of the Hall potential is directly linked to the boundary conditions at the injection source contact and requires a full account of electron-electron interactions [1].

In conventional semiconductor structures and graphene, a very similar potential to the one obtained in the classical case has been observed by various potential mapping methods, such as scanning probe microscopy and the photoelectric effect. On the theoretical side, this finding is surprising and incompatible with both, the edge state picture of the QHE and the bulk disorder picture of delocalized/localized states [1, 2]. I discuss how the different theoretical models of the QHE depend on the choice of boundary conditions and why the result show in Fig. 1 requires to solve the current distribution in a completely self-consistent fashion (including the hot-spot region and interactions) for a finite Hall device [2]. Both, the finite size and the self-consistently are often lacking in mesoscopic models of transport in a strong magnetic field and pose tremendous computational challenges. The usage of massively parallel graphics processing units (GPU) is crucial to obtain a self-consistent picture already for the classical case [1] and holds great promises to speed up fully quantum-mechanical simulations. I discuss how GPU computing can be applied to mesoscopic systems in an efficient way [3].

References

[1] T. Kramer, V. Krueckl, E. Heller, and R. Parrott *Self-consistent calculation of electric potentials in Hall devices* Phys. Rev. B, 81, 205306 (2010).

[2] T. Kramer, C. Kreisbeck, V. Krueckl, E. Heller, R. Parrott, and C.-T. Liang *Theory of the quantum Hall effect in finite graphene devices* Phys. Rev. B **81**, 081410(R) (2010).

[3] T. Kramer *electronic resource: GPU program resources available at* `http://quantumdynamics.wordpress.com/gpu`

Hofstadter butterfly and a high field quantum spin Hall effect in graphene/hBN heterostructures

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Graphene is distinguished from conventional quantum Hall systems by its honeycomb lattice. The sublattice symmetry leads to the existence of a unique four-fold degenerate zero energy Landau level, in which lattice scale interactions can lead to a variety of novel isospin ferromagnetic states. However, graphene is even more promising from an experimental perspective, enabling device geometries and measurements difficult or impossible to realize in other two dimensional electronic systems. This poster describes two recent experiments in which we engineer new varieties of low dimensional systems in graphene.

In the first, experiment, we use the interplay between the graphene lattice and a slightly mismatched hBN substrate to engineer a moire superlattice. The spatially varying interlayer atomic registry results in a local breaking of the carbon sublattice symmetry, turning graphene into a semiconductor.
The long range moiré superlattice potential, meanwhile, allows us to observe the Hofstadter butterfly at the highest magnetic fields, characterized by the splitting of single Landau bands into topologically nontrivial subbands between which the Hall conductance oscillates between quantized values[1].

In the second experiment, we use extremely high in-plane magnetic fields to drive charge neutral graphene into a spin-polarized state that is enclosed by counterpropagating, helical edge states (see figure). The properties of the resulting helical edge states can be modulated by balancing the applied field against an intrinsic antiferromagnetic instability, which tends to spontaneously break the spin-rotation symmetry. In the resulting canted antiferromagnetic (CAF) state, we observe transport signatures of gapped edge states, which constitute a new kind of one-dimensional electronic system with tunable band gap and associated spin-texture.

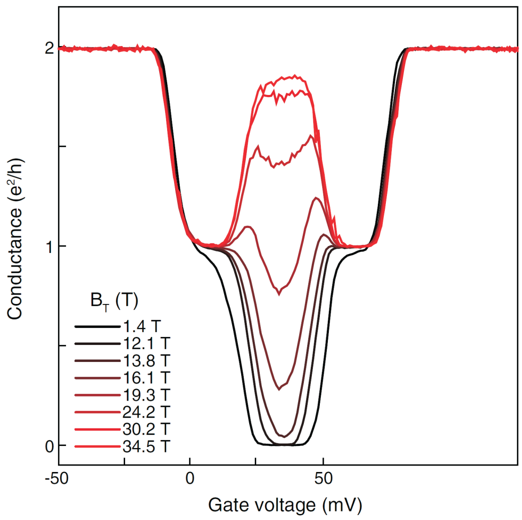

Figure 1: **Quantum spin Hall effect in spin polarized graphene.** Clean, charge neutral graphene subjected to a magnetic field is an insulator. A large in-plane field drives the $\nu = 0$ state from insulator to a conductor, characterized by $G \sim 2e^2/h$ conductance, an incompressible bulk, and helical, counterpropagating edge states.[2]

References

[1] B. Hunt et al., *Science*, (2013).

[2] A.F. Young et al., *In Preparation*, (2013).

Dynamic Nuclear Polarization by Breakdown of Quantum Hall Effect in an InGaAs Quantum Well

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The nuclear polarization of Ga and As nuclei has been widely studied in GaAs/AlGaAs heterostructures [1]. In these systems, for certain quantum Hall states, the electrons can be used to polarize the nuclear spins of the host material through the hyperfine interaction. The control of nuclear spins is currently of widespread interest in the context of quantum information processing [1]. Motivated by the recent study of Kawamura *et al.* on dynamic nuclear polarization (DNP) induced by the breakdown of the quantum Hall effect in GaAs/$Al_{0.3}Ga_{0.7}As$ single heterostructure[2], we looked for DNP by this effect in InP/$In_{0.76}Ga_{0.24}As$ quantum well Hall bars. In contrast to Ga and As, each of which have a nuclear spin of 3/2, In has a larger nuclear spin of 9/2.

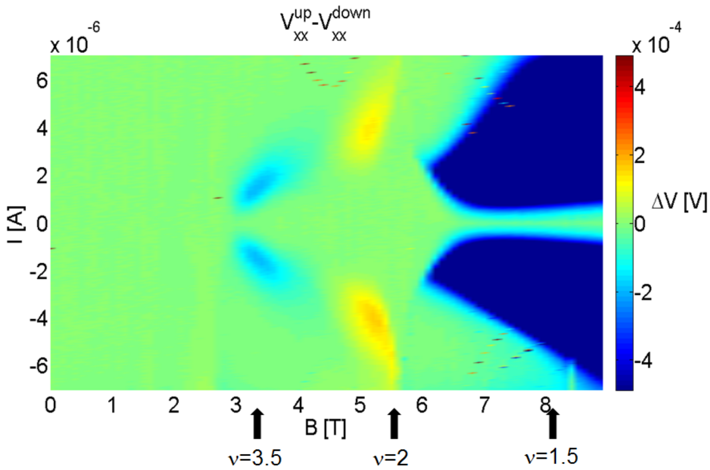

Figure 1: Hysteresis revealed in map of difference in voltage drop along a 15μm-wide Hall bar (V_{xx}) on sweeping the current and stepping the magnetic field. Arrows indicate the magnetic fields of the corresponding filling factors.

We analyzed the magnetoresistance of narrow Hall bars from an InP/InGaAs quantum well heterostructure. In the quantum Hall breakdown regime, we observed several distinct hysteretic features at certain filling factors which we attribute to DNP. These features are illustrated in figure 1, where we show the difference in longitudinal voltage drop on sweeping the current up and down. Most notably we observed a strong hysteretic feature around ν=1.5, and weaker features near ν=2 and ν=3.5. These features are different from those reported in Ref.[2]. We also found that when the current is switched abruptly from zero to 2μA near the ν=1.5 feature, V_{xx} rises steady on a time scale of several minutes in a manner that also depends strongly on the wait time at zero current.

References

[1] Y. Hirayama, G. Yusa, K. Hashimoto, N. Kumada, T. Ota, and K. Muraki, Semicond. Sci. Technol. **24** 023001 (2009).

[2] M. Kawamura, K. Kono, Y. Hashimoto, S. Katsumoto, and T. Machida, Phys. Rev. B **83**, 041305 (2011).

Landau level crossing and anti-crossing in Ge/SiGe bilayer two-dimensional hole systems

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Recent development of crystal growth technology enables us to fabricate high mobility two-dimentional hole gas (2DHG) systems. Particularly, the 2DHG in strained Ge is remarkable since it reveals large hole mobility and small effective mass almost comparable to that of electron. However, there have been only few studies on the quantum Hall effect (QHE) and its angular dependence in 2DHG based on a strained Ge/SiGe quantum well (QW). In this work, we study Landau level (LL) crossing and anti-crossing in bilayer 2DHG in Ge/SiGe QW.

A QW consisting of 20 nm $Si_{0.35}Ge_{0.65}$/20 nm Ge/20 nm $Si_{0.35}Ge_{0.65}$ was grown on SiGe/Si(001) virtual substrate by gas-source MBE. By introducing p-type doping on the top and bottom side of QW, bilayer 2DHG is created in the well. Longitudinal resistance were measured at 50 mK under the magnetic field perpendicular to the 2DHG. Resistance minima appeared at the filling factor 6, 10, 14,... because of the bilayer QHE. We measured magnetic field angle dependence of longitudinal resistance, which periodically changes due to the crossing of the Landau levels. Up to the third LL crossing was observed within our measurement range. This is very distinct from single layer Ge/SiGe 2DHG where the LL crossing was not observed within the same magnetic field range.

We also observed anti-crossing of the LLs. Furthermore, a weak anti-localization was observed in the low-field data of longitudinal resistance. We discuss the LL anti-crossing in terms of the cubic Rashba spin-orbit interaction in the Ge/SiGe 2DHG.

Fractional quantum Hall effect at 9/2 and 11/2 in wide quantum wells and bilayers

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The state at filling factors 9/2 and 11/2 in a two-dimensional electron system is known to exhibit anisotropic resistance, presumably indicating the presence of a stripe phase. We study, in a realistic treatment, the possibility of several candidate fractional quantum Hall states as a function of the the quantum well width and the electron density, and find that there is an experimentally accessible region where fractional quantum Hall effect can occur, described by a “subband 331” state. We also study a bilayer system, and find that the 331 phase is unlikely.

Luttinger parameters of interacting fermions in 1D beyond the low energy limit

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Interactions between electrons in one-dimension are fully described at low energies by only a few parameters of the Tomonaga-Luttinger model which is based on linearisation of the spectrum. We consider a model of spinless fermions with a short range interaction via the Bethe-Ansatz technique and show that a Luttinger parameter emerges in an observable beyond the low energy limit. A distinct feature of the spectral function, the edge that marks the lowest possible excitation energy for a given momentum, is parabolic for arbitrary momenta and the prefactor is a function of the Luttinger parameter, K.

Equilibration of quantum Hall edge states by an Ohmic contact

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Ohmic contacts are crucial elements of electron optics that have not received a clear theoretical description yet. We propose a model of an Ohmic contact as a piece of metal of the finite capacitance C attached to a quantum Hall edge. It is shown that charged quantum Hall edge states may have weak coupling to neutral excitations in an Ohmic contact. Consequently, despite being a reservoir of neutral excitations, an Ohmic contact is not able to efficiently equilibrate edge states if its temperature is smaller than $\hbar\Omega_c$, where Ω_c is the inverse RC time of the contact. This energy scale for a floating contact may become as large as the single-electron charging energy e^2/C. Experimental investigations of such regime are underway [1].

References

[1] C. Altimiras et al., Phys. Rev. Lett. **105**, 226804 (2010).

Flux Quantization Due to Monopole and Dipole Currents

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By discussing field-induced quantum interference effects due to monopole moments and those due to dipole moments on equal footing, their similarities and differences are clarified. First, we demonstrate the general principle for flux quantization. For particles carrying a monopole moment, the interference causes monopole current to oscillate periodically with flux defined as inner product of field and area, whereas for particles carrying a fixed dipole moment, the dipole current oscillates periodically with flux vector defined as cross product of field and trajectory. Our analysis unifies the oscillation of monopole or dipole currents in various devices, such as SQUID and spin-FET[1], into the same physical picture. Second, we show that interference effects can also happen in open trajectory devices that transport dipole currents, such as spin Josephson effect[2], based on the non-gauge field nature of the interference effects of dipole moments. In ad dition, we propose that the interference effect of electric dipoles, known as He-McKellar-Wilkens effect[3, 4], can be realized by the exciton condensates observed in bilayer quantum Hall systems[5] and bilayer graphene[6]. We further propose a dc SQUID-like device to measure the interference effect of the exciton condensate, as shown in Figure 1.

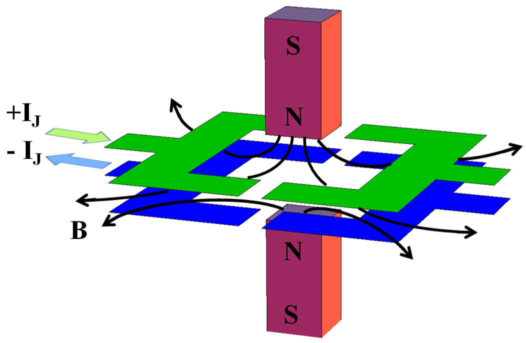

Figure 1: Proposed dc SQUID-like device that uses He-McKellar-Wilkens effect to create interference of bilayer exciton condensates. The green and blue sheets indicate the quantum Hall bilayer or bilayer graphene. The two oppositely placed magnets create a magnetic field that passes the space between the two layers, and cause a flux difference in the blue and green trajectories. The $\pm I_J$ indicates the counterflow experiment to measure the current.

References

[1] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[2] F. S. Nogueira and K.-H. Bennemann, Europhys. Lett. **67**, 620 (2004).
[3] X.-G. He and B. H. J. McKellar, Phys. Rev. A **47**, 3424 (1993).
[4] M. Wilkens, Phys. Rev. Lett. **72**, 5 (1994).
[5] I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **84**, 5808 (2000); Phys. Rev. Lett. **87**, 036803 (2001)
[6] S. Kim, I. Jo, J. Nah, Z. Yao, S. K. Banerjee, and E. Tutuc, Phys. Rev. B **83**, 161401(R) (2011).

Proposal for the detection and braiding of Majorana fermions in a quantum spin Hall insulator

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We show how a quantum dot with a ballistic single-channel point contact to a superconductor can be created by means of a gate electrode at the edge of a quantum spin Hall insulator (such as an InAs/GaSb quantum well). A weak perpendicular magnetic field traps a Majorana zero-mode, so that it can be observed in the gate-voltage-averaged differential conductance $\langle dI/dV \rangle$ as a $4e^2/h$ zero-bias peak above a $(\frac{2}{3}\pi^2 - 4)e^2/h$ background. The one-dimensional edge does not permit the braiding of pairs of Majorana fermions, but this obstacle can be overcome by coupling opposite edges at a constriction, allowing for a demonstration of non-Abelian statistics.

Enhanced Infrared Magneto-Optical Response of the Nonmagnetic Semiconductor BiTeI Driven by Bulk Rashba Splitting

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We study the magneto-optical (MO) response of the polar semiconductor BiTeI with giant bulk Rashba spin splitting at various carrier densities. Despite being nonmagnetic, the material is found to yield a huge MO activity in the infrared region under moderate magnetic fields (up to 3 T). Our first-principles calculations show that the enhanced MO response of BiTeI comes mainly from the intraband transitions between the Rashba-split bulk conduction bands. These transitions connecting electronic states with opposite spin directions become active due to the presence of strong spin-orbit interaction and give rise to distinct features in the MO spectra with a systematic doping dependence. We predict an even more pronounced enhancement in the low-energy MO response and dc Hall effect near the crossing (Dirac) point of the conduction bands [1].

References

[1] L. Demkó, G. A. H. Schober, V. Kocsis, M. S. Bahramy, H. Murakawa, J. S. Lee, I. Kézsmárki, R. Arita, N. Nagaosa, Y. Tokura, Phys. Rev. Lett. **109**, 167401 (2012).

Phase-locked magnetoconductance oscillations as a probe of Majorana edge states

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We calculate the Andreev conductance of a superconducting ring interrupted by a flux-biased Josephson junction, searching for electrical signatures of circulating edge states. Two-dimensional pair potentials of spin-singlet d-wave and spin-triplet p-wave symmetry support, respectively, (chiral) Dirac modes and (chiral or helical) Majorana modes. These produce h/e-periodic magnetoconductance oscillations of amplitude $\simeq (e^2/h)N^{-1/2}$, measured via an N-mode point contact at the inner or outer perimeter of the grounded ring. For Dirac modes the oscillations in the two contacts are independent, while for an unpaired Majorana mode they are phase locked by a topological phase transition at the Josephson junction.

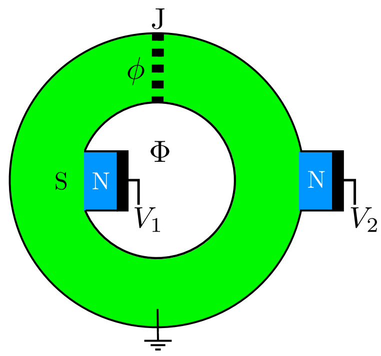

Figure 1: Superconducting ring (S) containing a weak link (J), forming a flux-biased Josephson junction. A current can be injected into the grounded superconductor from a voltage-biased normal-metal (N) contact at the inner or outer perimeter. The Andreev conductance $G_n = I/V_n$ is the ratio of the current-to-ground I and the applied voltage V_n to contact $n = 1, 2$ (with $V = 0$ for the other contact).

References

[1] G. E. Volovik, JETP Lett. **66**, 522 (1997).
[2] T. Senthil, J. B. Marston, and M. P. A. Fisher, Phys. Rev. B **60**, 4245 (1999).
[3] N. Read and D. Green, Phys. Rev. B **61**, 10267 (2000).
[4] A. P. Mackenzie and Y. Maeno, Rev. Mod. Phys. **75**, 657 (2003).
[5] R. Nandkishore, L. Levitov, and A. Chubukov, Nature Phys. **8**, 158 (2012).
[6] L. Fu and C. L. Kane, Phys. Rev. Lett. **100**, 096407 (2008).
[7] S. Ryu, A. Schnyder, A. Furusaki, and A. Ludwig, New J. Phys. **12**, 065010 (2010).
[8] K. T. Law, P. A. Lee, and T. K. Ng, Phys. Rev. Lett. **103**, 237001 (2009).
[9] B. J. Wieder, F. Zhang, and C. L. Kane, arXiv:1302.2113.

Dependence of the bistability effect in microwave-irradiated two-dimensional electron systems on the radiation frequency

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The bistability effect [1] recently observed in the microwave-induced zero-resistance state [2, 3] of two-dimensional electron systems (2DES) gives a strong argument in favor of sponteneous symmetry breaking as the origin of this state predicted in Ref. [4]. The effect manifests itself as a spontaneous irregular switching of a microwave-induced photovoltage between two different values. The photovoltage is detected between nonequivalent heavily doped contacts, one surrounded by the 2DES (inner contact) and the other located on the mesa perimeter (outer contact). The use of a set of inner contacts proves the simultaneous switching of the microwave induced dc electric field in nearly all of the sample. The effect was initially observed for several narrow ranges of the microwave frequency only. Here, we report an extensive study of the frequency dependence.

We found that the bistability can be observed in a much wider range of frequencies, if the temperature is increased from 0.5 K to 1.3 K. However the effect retains its very high sensitivity to the frequency (see Fig.1), which can't be attributed to a variation of the microwave power. The bistability effect was also found to be highly sensitive to the microwave field configuration, which may cause the observed frequency dependence. The latter observation is rather surprising, since the microwave wavelength essentially exceeds the sample size. The physical origin of the observed bistability therefore still awaits a theoretical explanation.

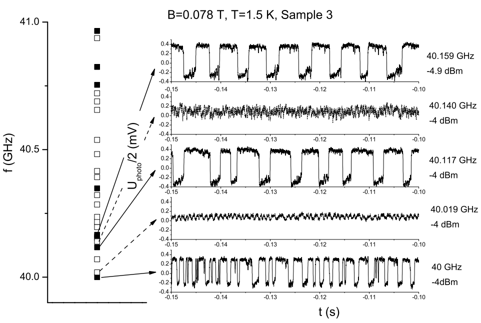

Figure 1: The most pronounced pulsed photovoltage traces observed for different microwave frequencies and powers.

References

[1] S.I. Dorozhkin, L. Pfeiffer, K. West, K. von Klitzing, and J.H. Smet, Nature Physics, **7**, 336 (2011).

[2] R.G. Mani, J.H. Smet, K. von Klitzing, V. Narayanamurti, W.B. Jonson, and V. Umansky, Nature **420**, 646 (2002).

[3] M.A. Zudov, R.R. Du, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **90**, 046807 (2003).

[4] A.V. Andreev, I.L. Aleiner, and A.J. Millis, Phys. Rev. Lett. **91**, 056803 (2003).

Evidence for two-dimensional Wigner crystal formation in chemical potential measurements

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The evolution of the chemical potential of a 2-dimensional electron system was investigated within the quantized Hall regime. The measurement of this thermodynamic quantity was carried out using a closely spaced GaAs bilayer system, with top and bottom gates as well as separate contacts to each layer. Chemical potential variations in one layer were detected with high resolution by monitoring the induced resistance change in the neighboring layer [1, 2]. Apart from the well known rapid increase of the chemical potential when the lower lying Landau level became completely occupied and a higher lying Landau level got filled, two additional anomalies manifested themselves symmetrically around exact integer filling (Fig. 1 (a)). They were attributed to the formation of incompressible Wigner crystals of either quasiparticles or quasiholes [3]. Non-equilibrium dynamics was excluded as the origin of the extra jumps in the chemical potential [4].

The investigations were carried out at different densities, i.e. magnetic fields as well as temperatures. The ratio of the magnetic length l_B over the interparticle distance $l^* = 1/\sqrt{n^*}$ (n^* is the density of quasiparticles) did not vary with the B-field (Fig. 1 (b)). The anomalies vanished when the temperature exceeded around 400 mK, which is consistent with the melting behavior of a solid. More interestingly, the two anomalies got closer to the exact integer filling at higher temperatures. A linear extrapolation (Fig. 1 (c)) yields a temperature of 840 mK which marks the critical temperature for a Wigner crystal.

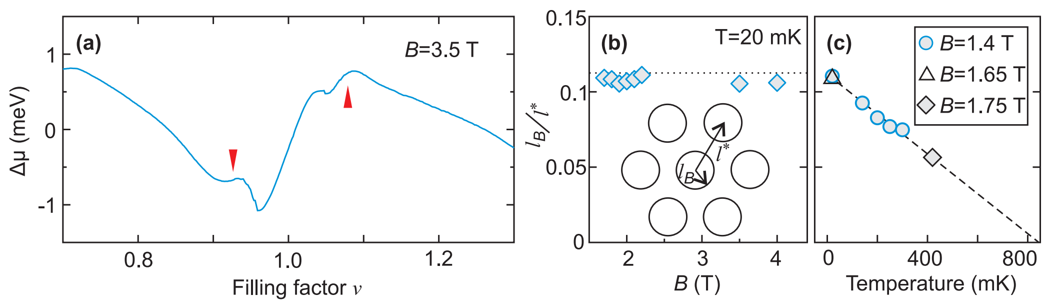

Figure 1: (a) Chemical potential measured around filling factor $\nu = 1$ at $B = 3.5$ T. Arrows mark the two anomalous features indicating the incompressible state of the Wigner crystal. (b)(c) Critical ratio l_B/l^* at which the anomalies appear plotted as a function of (b) the magnetic field B and (c) the temperature. Inset to (b) illustrates the two length scales: l_B–the magnetic length; l^*–the quasiparticle distance. Dotted line marks $l^*/l_B = 9$. Dashed line linearly extrapolates to a temperature of 840 mK at $l_B/l^* = 0$.

References

[1] L. H. Ho, et al., Appl. Phys. Lett. **96**, 212102 (2010).
[2] S. Kim, et al., Phys. Rev. Lett. **108**, 116404 (2012).
[3] Y. Chen, et al., Phys. Rev. Lett. **91**, 016801 (2003).
[4] L. H. Ho, et al., Phys. Rev. B **82**, 153305 (2010). E. Tutuc, et al., Phys. Rev. B **68**, 201308 (2003). W. Pan, et al., Phys. Rev. B. **71**, 153307 (2005).

Role of coherent state superpositions in the bipolar spin blockade of a triple quantum dot

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Spin (or Pauli) blockade[1] is commonly employed in double quantum dot spin qubit devices as the critical element in the spin to charge detection process in Electron Spin Resonance , Electron Dipole Spin Resonance and in general, in spin qubit manipulation experiments. In spin blockade transport measurements in double quantum dots, the electrical current flows freely in one direction, but is blockaded in the other due to the Pauli exclusion principle. The blockade is found to be not perfect at zero magnetic field due to a mixing of singlet and triplet states in a field gradient resulting from the hyperfine interactions. These leakage currents have been studied in detail and are dramatically suppressed when a small external magnetic field splits off the triplet states with parallel spins from the singlet state. We present experimental and theoretical investigations of the equivalent process in triple quantum dots (TQD) in series. We find novel leakage mechanisms due to coherent transport in TQD states. We demonstrate that as predicted [2, 3] current only flows through the TQD system when four charge configurations are degenerate, i.e. at quadruple points. We focus on one specific quadruple point where configurations of four and five electrons are degenerate. When a bias is applied in a magnetic field beyond 10mT bipolar spin blockade is observed where current is suppressed independent of the applied bias direction. As the field is reduced to zero spin blockade leakage resonances are observed within the transport region. Of special interest are two very sharp resonances which correspond to triple dot conditions when states in the left and right dot but not the center dot align. One of these resonances is found itself to involve bipolar spin blockade whilst the other does not. The resonances are found to result from a purely quantum coherent effect: electrons occupy states that involve their transference from one extreme to the other of the triple quantum dot without ever visiting the center. Such states have been invoked theoretically for possible applications such as spin bussing or quantum rectification[4]. Our theoretical model is based on the density matrix formalism allowing a description of the coherent dynamics within the quantum dot system as well as the electronic transport due to tunnel couplings to the leads. Our calculations accurately reproduce all the experimental transport features for the different configurations that unambiguously show bipolar spin blockade. The inspection of the off diagonal elements of the stationary density matrix proves that in fact, the left-right resonances stem from a purely coherent process between the left and right dots, that almost entirely avoids the passage of an electron tunneling through the center dot [5].

References

[1] K. Ono et al., Science **297**, 5585, (2002).
[2] M. C. Rogge et al., Physical Review B **77**, 193306 (2008).
[3] G. Granger et al., Physical Review B **82**, 075304(2010).
[4] A.D. Greentree et al., Physical Review B **70**,235317 (2004).
[5] M. Busl et al., Nature Nanotechnology, 8, **261** (2013).

Investigation of the quantum Hall effect in scalable graphene for metrology

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The quantum Hall effect (QHE) observed in graphene is promising for an application to metrology. Its robustness is an advantage to develop a resistance standard surpassing the GaAs-based in operating at $B \approx 2$ T, at $T > 4$ K and with higher measurement currents. This would ease the dissemination of the quantum resistance standard. Besides, graphene can be used for a fundamental test of the QHE universality, useful for the SI redefinition.

Although we achieved a measurement of the quantized Hall resistance with a 5×10^{-7} accuracy both in mono and bilayer exfoliated graphene deposited on SiO2/Si[1], our work evidenced limitations of such devices: their small size and the presence of charged impurities in the substrate result in low QHE breakdown currents via quasi-elastic inter-Landau level scattering. It also confirmed that obtaining large area graphene with controlled environment to get high charge carrier mobility (10000 $cm^2V^{-1}s^{-1}$) and homogeneous low carrier density (10^{11} cm^{-2}) is a prerequisite for the resistance metrology application.

We are now investigating the QHE in graphene produced by scalable techniques. In graphene grown by sublimation of SiC substrate, a transition between a localized regime and the quantum Hall regime is observed in low mobility sample[2, 3]. Higher mobility samples (> 8000 $cm^2V^{-1}s^{-1}$) exhibit a nice QHE with large breakdown current densities (collaboration with A. Ouerghi's group of LPN-CNRS). Figure 1 shows the QHE which was also observed in graphene grown by CVD on copper (collaboration with Vincent Bouchiat's group of Institut Nel). Measurements of the transport properties in the QHE regime as a function of temperature, magnetic field and current seem to point out grain boundaries in polycrystalline graphene enhancing dissipation

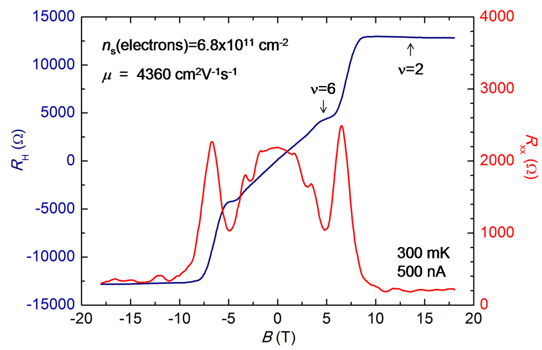

Figure 1: Transverse and longitudinal magnetoresistances in a Hall bar fabricated from monolayer graphene grown by CVD on Cu and transferred on Si/SiO_2.

References

[1] J. Guignard, D. Leprat, D. C. Glattli, F. Schopfer, and W. Poirier, Phys. Rev. B **85**, 165420 (2012).

[2] E. Pallecchi, M. Ridene, D. Kazasis, C. Mathieu, F. Schopfer, W. Poirier, D. Mailly, and A. Ouerghi, Appl. Phys. Lett. **100**, 253109 (2012).

[3] E. Pallecchi, M. Ridene, D. Kazasis, F. Lafont, F. Schopfer, W. Poirier, M. O. Mailly, and A. Ouerghi, Scientific Reports **3**, 1791 (2013).

Majorana and Andreev bound states in topological wires in the proximity of superconductors [1]

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We study one-dimensional topological SN and SNS long junctions obtained by placing a topological insulating nanowire in the proximity of either one or two SC finite-size leads. Using the Majorana Polarization order parameter (MP) [2], we find that the extended Andreev bound states (ABS) of the normal part of the wire acquire a finite MP : for a finite-size SN junction the ABS spectrum exhibits a zero-energy extended state which carries a full Majorana fermion, while the ABS of long SNS junctions with phase difference transform into two zero-energy states carrying two Majorana fermions with the same MP. Given their extended character inside the whole normal link, and not only close to an interface, these Majorana-Andreev states can be directly detected in tunneling spectroscopy experiments

References

[1] D. Chevallier, D. Sticlet, P. Simon, and C. Bena, Phys. Rev. B 85, 235307 (2012).

[2] D. Sticlet, C. Bena, and P. Simon, Phys. Rev. Lett. 108, 096802 (2012).

Local breakdown of the quantum Hall effect in narrow single layer graphene Hall devices

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We have analyzed the breakdown of the quantum Hall effect in 1 μm wide Hall devices fabricated from an exfoliated monolayer graphene transferred on SiO_x. We have observed that the deviation of the Hall resistance from its quantized value is weakly dependent on the longitudinal resistivity up to a current density of 5 A/m, where the Hall resistance remains quantized even when the longitudinal resistance increases monotonously with the current. Then a collapse in the quantized resistance occurs while longitudinal resistance keeps its gradual increase. The exponential increase of the conductivity with respect to the current suggests impurity mediated inter-Landau level scattering as the mechanism of the breakdown. The results are interpreted as the strong variation of the breakdown behavior throughout the sample due to the randomly distributed scattering centers that mediates the breakdown.

A Natural Topological Insulator

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The earths crust and outer space are rich sources of technologically relevant materials which have found application in a wide range of fields. Well-established examples are diamond, one of the hardest known materials, or graphite as a suitable precursor of graphene. The ongoing drive to discover novel materials useful for (opto)electronic applications has recently drawn strong attention to topological insulators. Here, we report that Kawazulite, a mineral with the approximate composition $Bi_2(Te,Se)_2(Se,S)$, represents a naturally occurring topological insulator whose electronic properties compete well with those of its synthetic counterparts. Kawazulite flakes with a thickness of a few tens of nanometers were prepared by mechanical exfoliation. They exhibit a low intrinsic bulk doping level and correspondingly a sizable mobility of surface state carriers of more than 1000 $cm^2/(V\ s)$ at low temperature. Based on these findings, further minerals which due to their minimized defect densities display even better electronic characteristics may be identified in the future.

References

[1] P. Gehring, H. M. Benia, Y. Weng, R. Dinnebier, C. R. Ast, M. Burghard, and K. Kern, Nano Letters. **13**, 1179 (2013).

Anomalous resistance overshoot in the integer quantum Hall effect

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Here we report our experimental findings defined by smooth edge considering narrow Hall bars. We investigated the magneto-transport properties of intermediate mobility two-dimensional electron systems and analyzed results within the screening theory of the integer quantized Hall effect. A non-monotonic increase of Hall resistance at the low magnetic field ends of the quantized plateaus is observed, which is known as the overshoot effect. Unexpectedly, for Hall bars that are defined by shallow chemical etching the overshoot effect becomes more pronounced at elevated temperatures. We observe the overshoot effect at odd and even integer plateaus, favoring a spin independent explanation. In a second set of the experiments, we investigate the overshoot effect in a gate defined Hall bar and explicitly show that the amplitude of the overshoot effect can be directly controlled by gate voltages. We offer a comprehensive explanation based on scattering between evanescent incompressible channels.

Effect of Temperature on Transconductance Fluctuation in Graphene

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In this work we investigate temperature-caused decay of transconductance fluctuations in a significant number of graphene samples within large ranges of carrier density and magnetic field, while T varies from 1.2 K to 50 K. Surprisingly, in a vast majority of cases, a simple exponential decay function $\delta G(T) = \delta G_0 + \delta G \exp(-T/T_1)$ fitted our experimental data, plotted as temperature dependences of root mean square values, much better than the standard power low model expected for mesoscopic conductance fluctuations. This result is not yet well understood. Moreover, similar results are also found when T-decay of individual features of transconductance fluctuations is evaluated. However, at very low temperatures below 1.2 K, a very good agreement with the formula $\delta G(T) = \delta G_0\{1 - \exp(-T_K/T)\}$ that describes transport through a QD is observed Fig. 1.

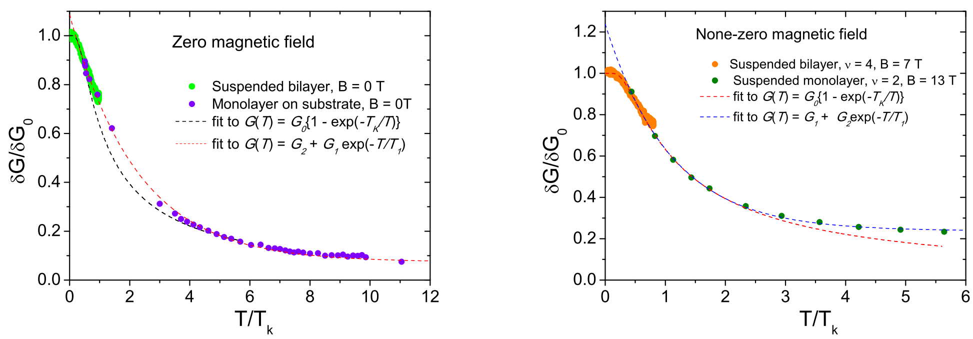

Figure 1: T-dependence of normalized conductance fluctuation amplitude a) without magnetic field and b) with magnetic field.

References

[1] Dong Su Lee, Viera Skákalová, R. Thomas Weitz, Klaus von Klitzing, and Jurgen H. Smet, Phys. Rev. Lett. **109**, 056602 (2012).

Spin-dependent thermoelectric transport in HgTe/CdTe quantum wells

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HgTe quantum wells are known to host, under a topological phase transition, the quantum spin Hall effect. The latter refers to the presence of metallic edge states moving in opposite direction for opposite spins. Recently, HgTe/CdTe quantum wells, among others topological insulators, have been proposed as good materials for thermoelectric conversion. The basic idea relies on the topological protection of the 1D edge states that prevents reduction of electrical transport in disordered systems. Their efficiency to convert heat into electricity is based on the dominance of the edge modes on transport [1,2]. On my present, I present the thermoelectric properties of HgTe/CdTe quantum wells through the analysis of Seebeck and spin Nernst coefficents in a four terminal cross-bar setup. As a lateral thermal gradient induces a longitudinal electric bias and a transverse spin current in such a system, each of them can be used as a probe of the topological regime as well as finite size effects of the quantum spin Hall insulator. Furthermore, I will present a qualitative relative between effective mass of particles and magnitude of spin Nernst signal which allows to provide an explanation of the observed phenomena based on anomalous velocities and spin-dependent scattering off boudaries [3] .

References

[1] R. Takahashi and S. Murakami, Phys. Rev. B **81**, 161302 (2010).

[2] O.A. Tretiakov, A. Abanov, S. Murakami, and J. Sinova, Appl. Phys. Lett. **97**, 073108 (2010).

[3] D.G. Rothe, E.M. Hankiewicz, B. Trauzettel, and M. Guigou, Phys. Rev. **B 86**, 165434 (2012).

MBE growth of high-quality Sb-based III-V semiconductor heterostructures

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Topological insulators characterized by a gapped bulk and counterpropagating edge modes in the presence of time reversal symmetry have been in the focus of interest since their theoretical prediction and subsequent experimental realizations in 3D (Bi_2Se_3, Sb_2Te_3 etc.) [1] and 2D (HgTe/CdTe) [2] and inspired a number of future applications, including spintronics, quantum computing and in combination with a superconductor: the generation of Majorana fermions [3].

Two-dimensional topological insulators can be realized in semiconductor systems that present bands inverted with respect to their usual arrangement by a strong spin-orbit coupling (HgTe) or by hybridization of neighboring electron and hole systems (combined InAs/GaSb quantum wells (CQWs) between AlSb barriers) according to theoretical calculations. So far, only the HgTe/CdTe system has been studied in detail. The InAs/GaSb CQW with its unique type II band alignment allows to tune the band gap of the hybridized electron-hole gas by electric fields and would allow to use the well-established III-V semiconductor technology [4].

First measurements of our samples show signs of this hybridization gap, i.e. a resistance resonance at the charge neutrality point where the electron density n $\approx$ p (hole density), which is a first step towards the observation of the Quantum Spin Hall Effect, further experiments are under way. We are interested in increasing the quality of our samples and optimizing their properties for large hybridization gaps.

A recently started area of research in our group is the fabrication of InSb quantum wells. Electrons in InSb have a smaller effective mass (0.0139 m_0), a larger g-factor (-51) and a narrower bandgap (0.17 eV) than in any other binary III-V semiconductor. Electron mobilities of up to 380'000 cm^2/Vs at low temperatures can be achieved [5] and the high g-factor results in a strong spin-orbit coupling making this material promising for applications in spintronics.

The growth of InSb/$Al_xIn_{1-x}Sb$ quantum wells on GaAs substrates with more than 14 % lattice mismatch is very challenging and $Al_xIn_{1-x}Sb$ with low Al concentrations between 10 % and 20 % has to be used as a barrier material for the lack of a lattice matched material with suitable energetic properties. The focus of the research thus lies on the optimization of the growth processes, sample structures and doping schemes.

First samples grown by our group show a mobility of 150'000 cm^2/Vs at 4 K with an electron density of 4.5×10^{11} cm^{-2}.

References

[1] Y. L. Chen et al., Science, **325**, 178 (2009).
[2] M. König et al., Science, **318**, 766 (2007).
[3] X.-L. Qi and S.-C. Zhang, Rev. Mod. Phys., **83**, 1057 (2011).
[4] C. Liu et al., Phys. Rev. Lett., **100**, 236601 (2008).
[5] S. J. Chung et al., Physica E, **7**, 807 (2000).

Single Molecule Magnets meet Graphene

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Graphene has a strong potential as component of novel spintronics devices. Pioneering experiments on graphene-based spinvalves have demonstrated long spin coherence lengths in this fascinating two-dimensional material. Besides its use as conducting channel for coherent spin transport, graphene is furthermore of interest for the detection and manipulation of the spin within molecular magnets. This task requires an appropriate coupling between the sheets and the single molecular magnets. Here, we describe the assembly of a functionalized Fe_4 cluster compound on graphene exploiting non-covalent π- stacking interaction, with focus on the molecules spatial arrangement in dependence of the deposition conditions and the type of graphene.

The obtained graphene/molecular magnet hybrids were thoroughly investigated by atomic force microscopy, matrix-assisted TOFMS, Raman spectroscopy, μ-SQUID measurements, as well as roomtemperature charge transport studies. We demonstrate the control over the organization of the molecules by tuning the deposition parameters (concentration of molecules, reaction time, cleaning procedure of the graphene prior to deposition) and the nature of the graphene sheet. Furthermore, the molecular layers were found to self-reorganize into molecular random networks when the sheets are subjected to external stimuli (e.g., slightly elevated temperature). The influence of the graphene environment on the magnetization dynamics of the molecular magnets is evidenced by μ-SQUID study at ultra low temperatures and a detailed theoretical model. Finally, preliminary non local spin-transport measurements at low-temperature are presented.

References

[1] L. Bogani *et al.*, Molecular spintronics using single-molecule magnets, Nature Materials **7**, 179 (2008).

[2] L. Bogani *et al.*, Single-Molecule-Magnet Carbon-Nanotube Hybrids, Angew. Chem. **121**, 760 (2009).

[3] M. Burghard *et.al.*, Carbon-Based Field-Effect Transistors for Nanoelectronics, Adv. Materials **21**, 2586 (2009).

[4] A. Cornia *et al.*, Energy-Barrier Enhancement by Ligand Substitution in Tetrairon (III) Single- Molecule Magnets, Angew. Chem. **116**, 1156 (2004).

[5] D. Gatteschi *et al.*, Quantum Tunneling of Magnetization and Related Phenomena in Molecular Materials, Angew. Chem. **42**, 268 (2003).

[6] H. Shin *et al.*, Efficient Reduction of Graphite Oxide by Sodium Borohydride and Its Effect on Electrical Conductance, Adv. Funct. Mat. **19**, 1987 (2009).

[7] Tombros *et al.*, Electronic spin transport and spin precession in single graphene layers at room temperature, Nature **448**, 571 (2007).

[8] D. A. Abanin *et al.*, Giant Nonlocality Near the Dirac Point in Graphene, Science **332**, 328 (2011).

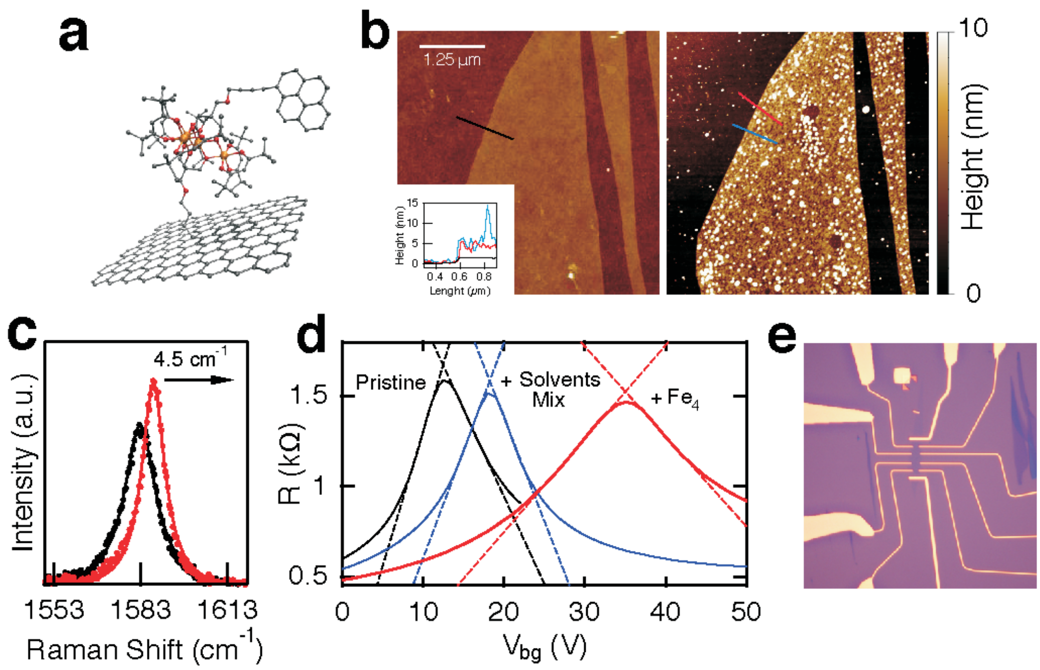

Figure 1: (a) Representation of Fe_4 SMM grafted on graphene through pyrene groups. (b) AFM analysis of a graphene flake before (left) and after (right) the wet-treatment with Fe_4. Inset: profile plot at the flake edge. (c) Influence of the functionalization on the Raman G-peak. (d) Charge transport properties of the pristine (black), treated with solvents (blue) and SMM functionalized (red) graphene. (e) Example of graphene-based device.

Quantum-Hall effect in graphene with point-like impurities

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We explore the longitudinal conductivity of graphene at the Dirac point in strong magnetic field with two types of short-range scatterers: adatoms that mix the valleys and scalar impurities that do not mix them. A scattering theory for the Dirac equation is employed to express the conductance of a graphene sample as a function of impurity coordinates; an averaging over positions of impurities is then performed numerically. The conductivity is equal to the ballistic value $\sigma \approx \pi^{-1}[4e^2/h]$ for each disorder realization provided the number of flux quanta considerably exceeds the number of impurities. For weaker fields, the conductivity in the presence of scalar impurities scales to the quantum-Hall critical point with $\sigma \approx 0.4\,[4e^2/h]$ at half filling or to zero away from half filling due to the onset of Anderson localization. For adatoms the localization behavior is obtained also at half filling due to splitting of the critical energy by intervalley scattering. Our results reveal a complex scaling flow governed by fixed points of different symmetry classes.

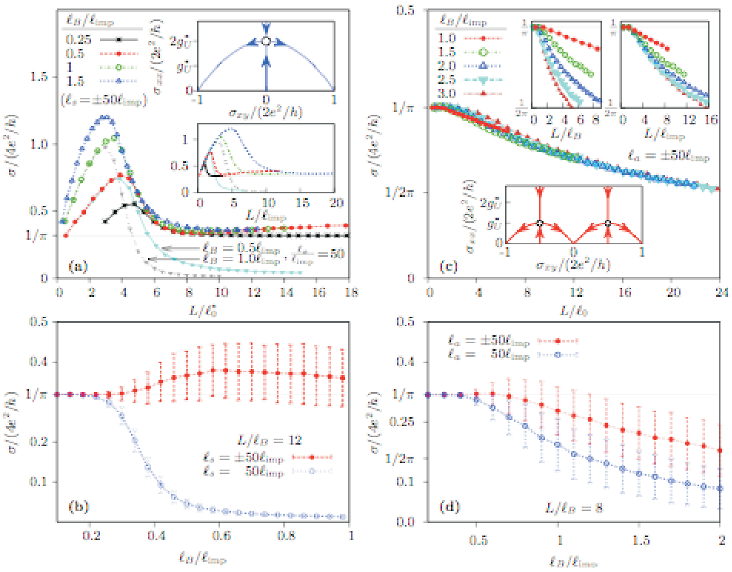

Figure 1: Longitudinal conductivity in a sample with point-like scalar impurities or adatoms as a function of system size. The aspect ratio W/L is kept constant, ℓ_s and ℓ_a are the scattering cross-section for the scalar impurities and ad-atoms, ℓ_B the magnetic length, and ℓ_{imp} is the average distance between impurities.

References

[1] P. M. Ostrovsky, M. Titov, S. Bera, I. V. Gornyi, and A. D. Mirlin, Phys. Rev. Lett. **105**, 266803 (2010).

[2] J. Schelter, P. M. Ostrovsky, I. V. Gornyi, B. Trauzettel, and M. Titov, Phys. Rev. Lett. **106**, 166806 (2011).

[3] M. Y. Azbel, Physica A: Stat. Mech. **200**, 491 (1993).

[4] P. M. Ostrovsky, I. V. Gornyi, and A. D. Mirlin, Phys. Rev. **B 77**, 195430 (2008).

Topological Insulating Phase in InAs/GaSb Manifested by Non-Local Transport

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In quantum Hall systems [1], the absence of backscattering due to the spatial separation of counterpropagating edge channels ensures robust quantization of Hall conductance. In contrast, in quantum spin Hall systems [2] or 2D topological insulators, the quantum spin Hall effect (QSHE) can be compromised by inelastic scattering that equilibrates counterpropagating channels on the same sample edge. This makes the experimental demonstration of topological insulating phase more difficult. Here we demonstrate non-local transport measurements that confirm the dominance of edge transport, even for incomplete conductance quantization. We show that the InAs/GaSb system [3, 4] can be tuned to a topological insulating (TI) phase with negligible bulk conductivity.

The samples studied are InAs (top)/GaSb (bottom) heterostructures sandwiched between AlGaSb barriers with varying InAs layer thickness (w = 10, 12, and 14 nm) grown on an n-type GaAs substrate that serves as a back gate. The Hall bars have six ohmic contacts with an edge channel length of 2 μm. A front gate metal is evaporated following an atomic-layer-deposited Al_2O_3 gate insulator. A longitudinal resistance (R_{xx}) maximum is observed for all the samples when the Fermi level is tuned to within the band gap via front gate voltage V_{FG}. For the $w = 10$ nm sample, the peak resistance increases with decreasing temperature (T) and reaches several MΩ at 0.25 K, indicating that the system is a fully gapped normal insulator. For the 14-nm sample, the low peak resistance of only 2 kΩ and the absence of T dependence indicate a semi-metallic band structure. In contrast, for the 12-nm sample, the low-T peak resistance saturates close to $h/2e^2$ (the quantized value expected for QSHE in the six-terminal geometry), but quantization is not achieved.

When the system is in a TI phase, the bulk conductance vanishes and transport is governed by edge channels. As a result, the system can be described by an equivalent circuit comprising six resistors connected in a ring configuration. We focus on the ratio between the resistance values measured with two adjacent pairs of voltage probes. In a TI phase, this ratio is sample specific and thus should not depend on the current injection path. Indeed, for the 12-nm sample, we find that the resistance ratios measured for different current injection paths coincide with each other, including V_{FG}-dependent fluctuations, over the V_{FG} range of the R_{xx} peak. Similar results have been confirmed for all contact configurations.

References

[1] K. von Klitzing *et. al.*, Phys. Rev. Lett. **45**, 494 (1980).
[2] M. König *et. al.*, Science **318**, 766 (2009); A. Roth *et. al.*, Science **325**, 294 (2009).
[3] C. Liu *et. al.*, Phys. Rev. Lett. **100**, 236601 (2008).
[4] I. Knez *et. al.*, Phys. Rev. Lett. **107**, 136603 (2011).

Effect of electron-electron interactions in thermoelectric power in graphene

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Thermoelectric power (TEP) of graphene is previously measured in the disorder limited transport regime where the semiclassical Mott relation agrees with experimental data. Here, we report the TEP measurement on graphene samples deposited on hexa boron nitride substrates where drastic suppression of disorder is achieved. Our results show that at high temperatures where the inelastic scattering rate due to electron-electron (e-e) interactions is higher than the elastic scattering rate by disorders, the measured TEP exhibit a large enhancement compared to the expected TEP from the Mott relation. We also investigated TEP in the quantum Hall regime at a high magnetic fields, where we observed symmetry broken integer quantum Hall due to the strong e-e interactions. The field dependence of TEP at these states reveals the important role that exchange interactions play.

Exactly solvable 1D lattice model for the fractional quantum Hall states with matrix-product ground states

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We introduce a one-dimensional lattice model with an exact matrix-product ground state describing the fractional quantum Hall (FQH) states in Laughlin series (filling factors $\nu = 1/q$) on torus geometry. Surprisingly, the exactly solvable Hamiltonian has the same mathematical structure as that of the pseudo potential for the Laughlin wave function, and naturally derives the general properties of the Laughlin state such as the Z_2 properties of the FQH states and the fermion-boson relation. The obtained exact ground states have high overlaps with the Laughlin states and well describe their properties. Using matrix product method, density functions and correlation functions are calculated analytically. Especially, obtained entanglement spectra reflect gapless edge states as was discussed by Li and Haldane. We also obtained magneto-roton behaviour in the excited states based on the variational matrix-product wave functions.

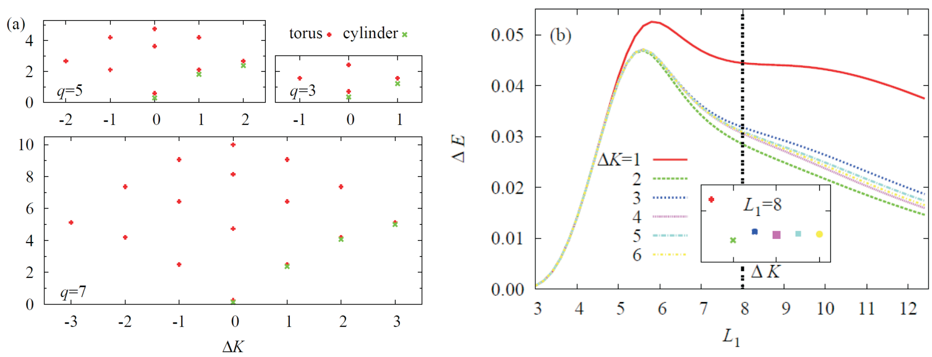

Figure 1: (a) Entanglement spectra (as functions of momentum) of obtained by the matrix-product method which reflect chiral (non-chiral) Tomonaga-Luttinger liquid behaviour for cylinder (torus) geometry. (b) Excitation energies for various momenta obtained by variational matrix product wave function.

References

[1] M. Nakamura, Z.-Y. Wang, and E. J. Bergholtz, Phys. Rev. Lett. **109**, 016401 (2012).

[2] Z.-Y. Wang and M. Nakamura, arXiv:1206.3071.

[3] Z.-Y. Wang and M. Nakamura, arXiv:1301.7549.

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Photovoltaic Infrared Photoresponse of the High-Mobility Graphene Quantum Hall System due to Cyclotron Resonance

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Even denominator fractional quantum Hall states in ZnO

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A Natural Topological Insulator

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