OIST – NPCQS2012, Naha, Japan
April 26, 2012

Zero-resistance states induced by electromagnetic wave excitation in 2D electron systems

Ramesh Mani

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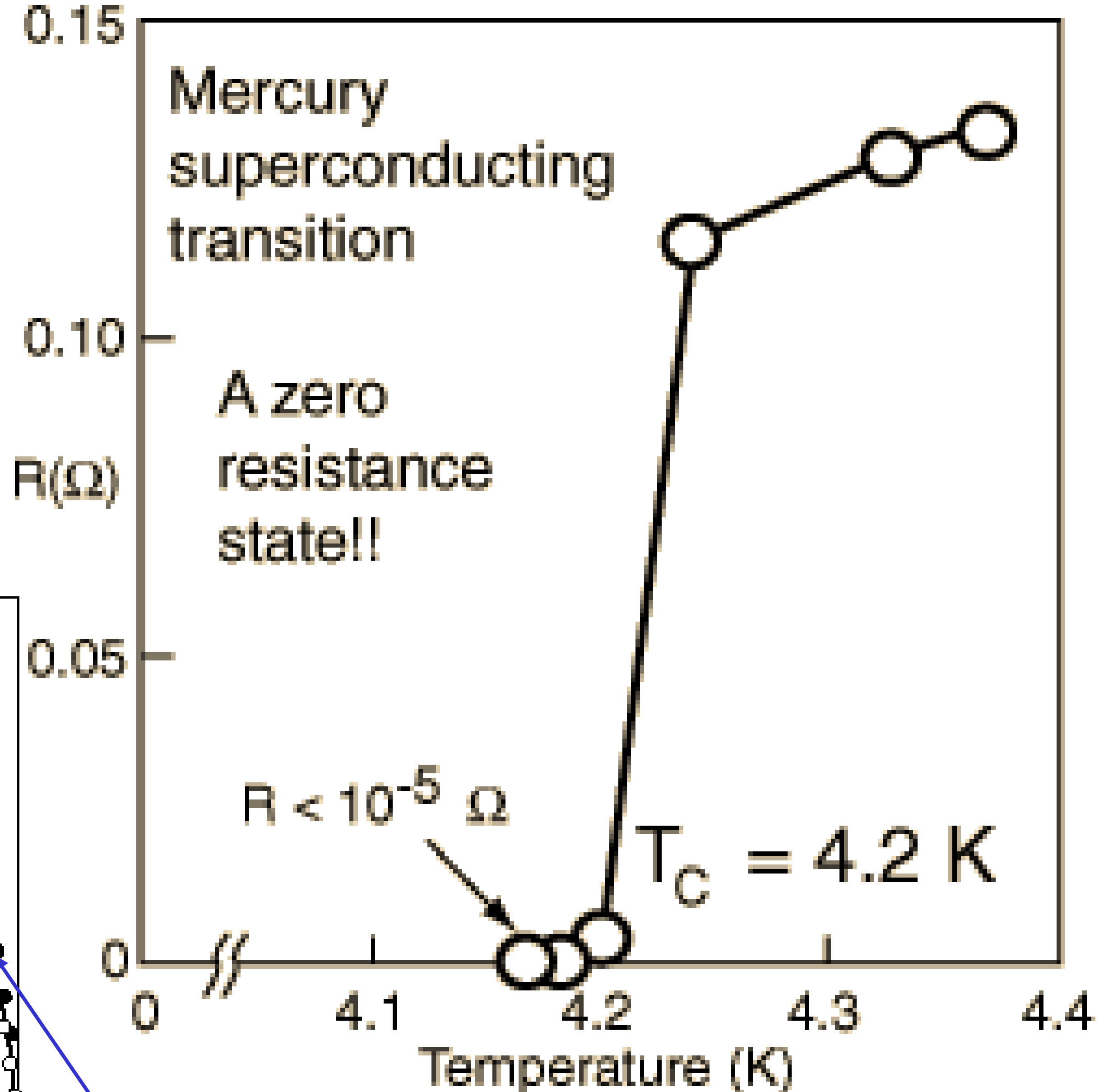
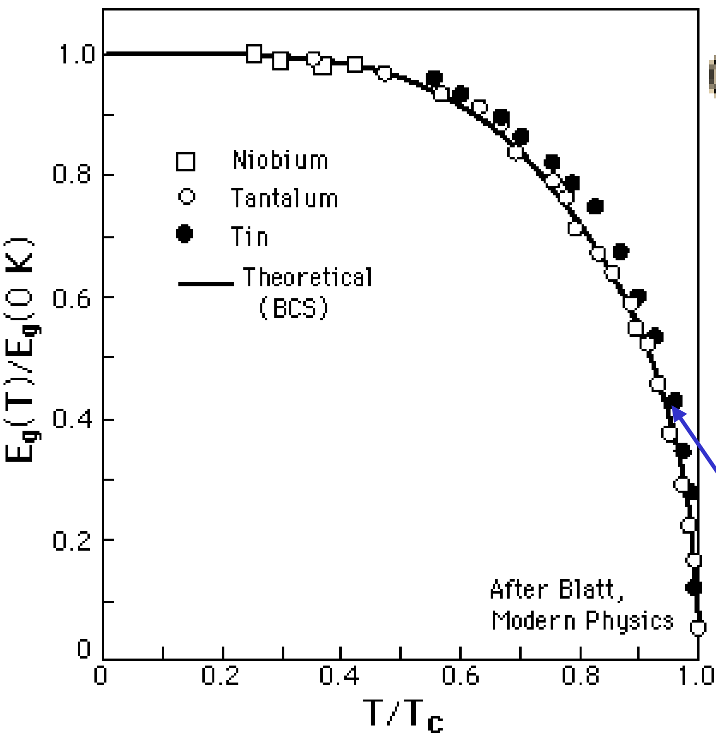
K. Onnes





Energy Gap

PHYSICAL REVIEW B VOLUME 25, NUMBER 2 15 JANUARY 1982

Zero-resistance state of two-dimensional electrons in a quantizing magnetic field

D. C. Tsui, H. L. Störmer, and A. C. Gossard
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 30 October 1981)

When the Fermi level is pinned in the energy gap between two Landau levels of two-dimensional electrons, the response of electrons in the completely filled levels to an electric field is a dissipation-free Hall current perpendicular to the field. Our low-temperature measurements on GaAs-$Al_xGa_{1-x}As$ heterojunctions give an upper limit for the resistance along the current path of $\rho_{xx} \lesssim 5 \times 10^{-7}$ $\Omega/\square$ which corresponds to a three-dimensional resistivity of $\rho \lesssim 5 \times 10^{-13}$ Ω cm. This resistivity is more than one order of magnitude lower than the resistivity of any nonsuperconducting material.

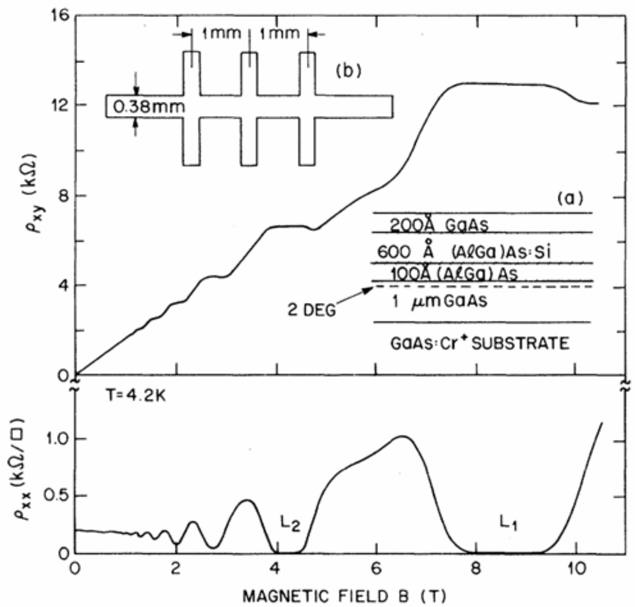
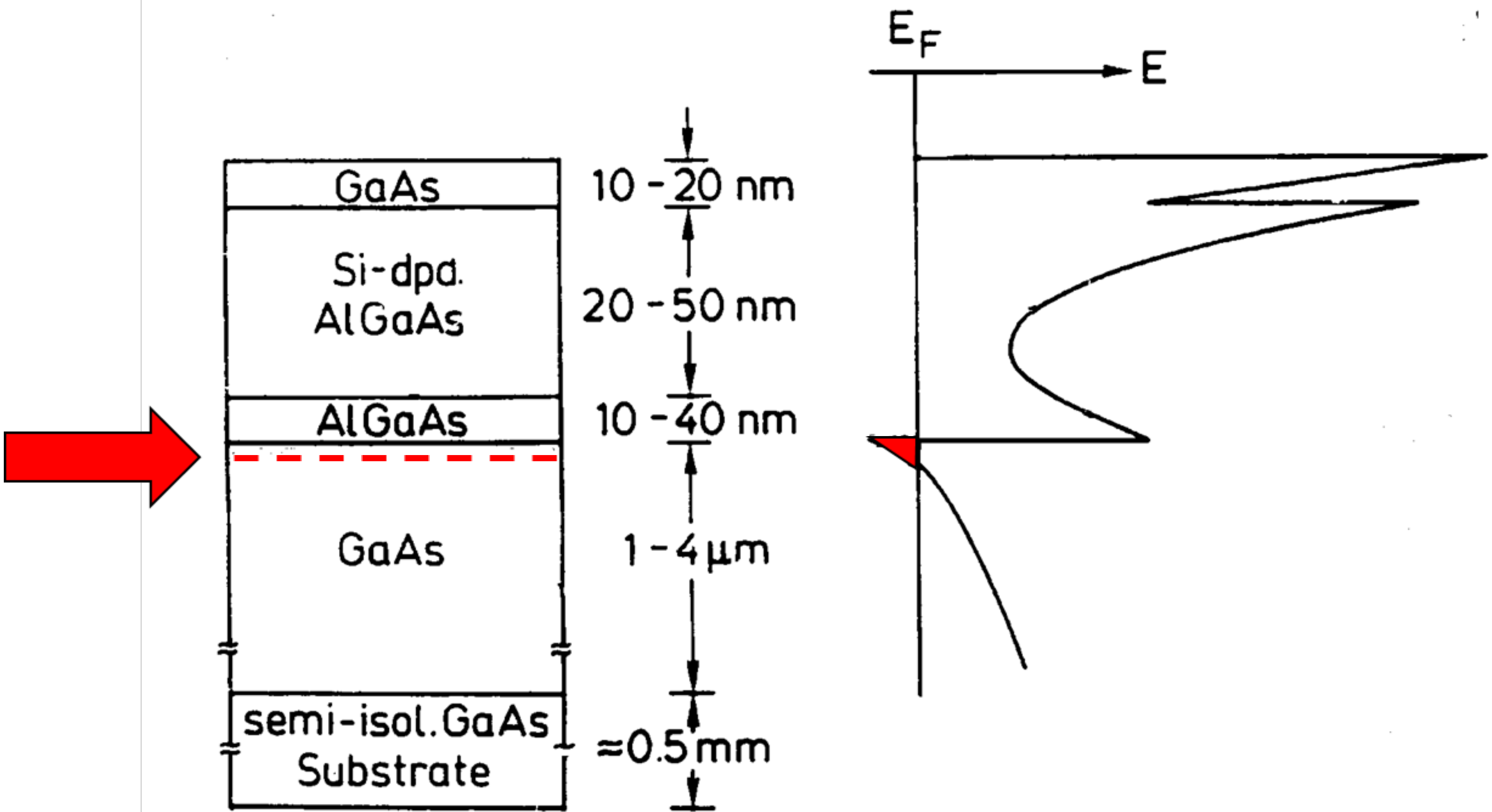


FIG. 1. A survey over the field dependence of ρ_{xy} and ρ_{xx} of a GaAs-$Al_xGa_{1-x}As$ heterojunction at 4.2 K (taken from Ref. 4). Insert (a) shows the dimensions and constituents of the sample and insert (b) shows the geometry of the "Hall bridge."

The GaAs/AlGaAs heterostructure includes two-dimensional electrons



GaAs/AlGaAs system provides nature's perfect interface for:

" electrons in flatland"

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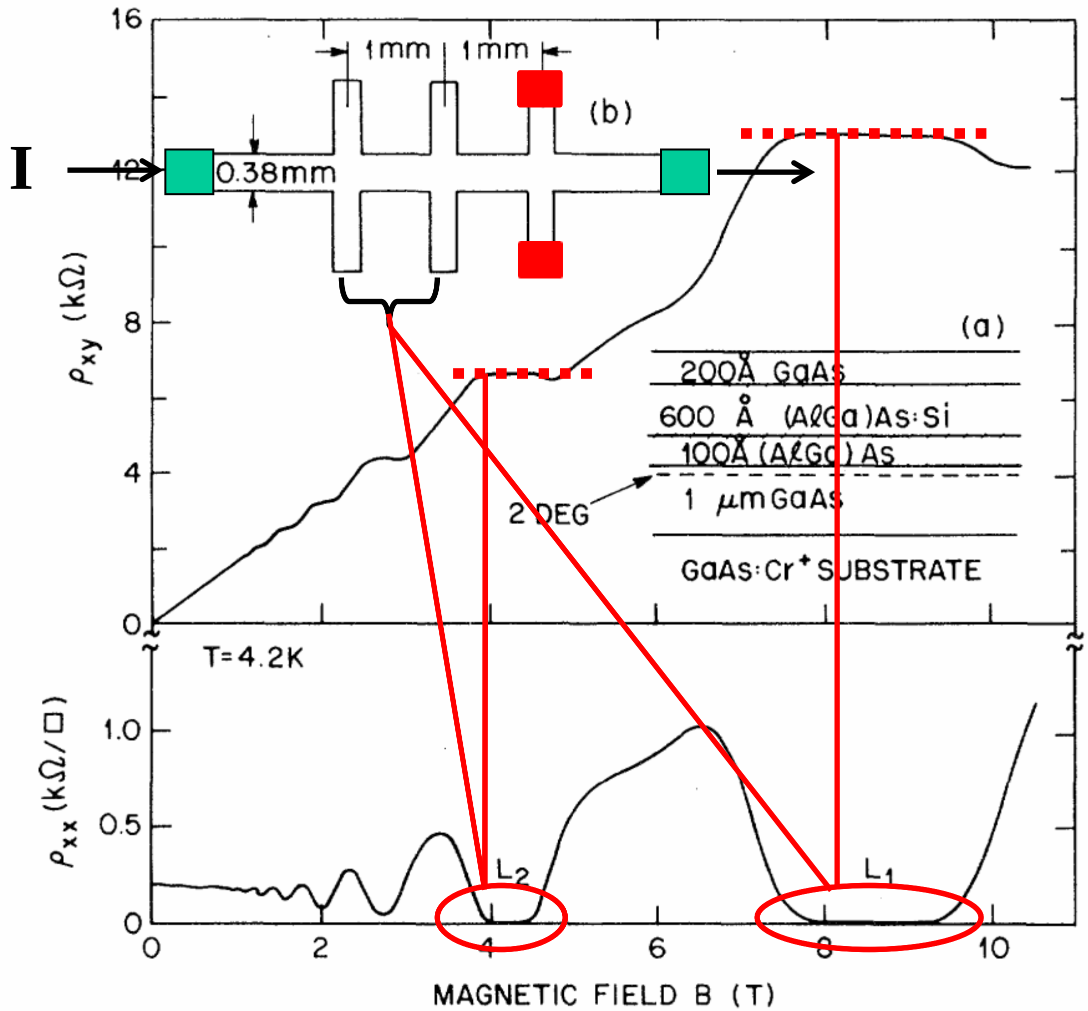


VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

K. v. Klitzing
Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and
Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France

and

G. Dorda
Forschungslaboratorien der Siemens AG, D-8000 München, Federal Republic of Germany

and

M. Pepper
Cavendish Laboratory, Cambridge CB3 0HE, United Kingdom
(Received 30 May 1980)

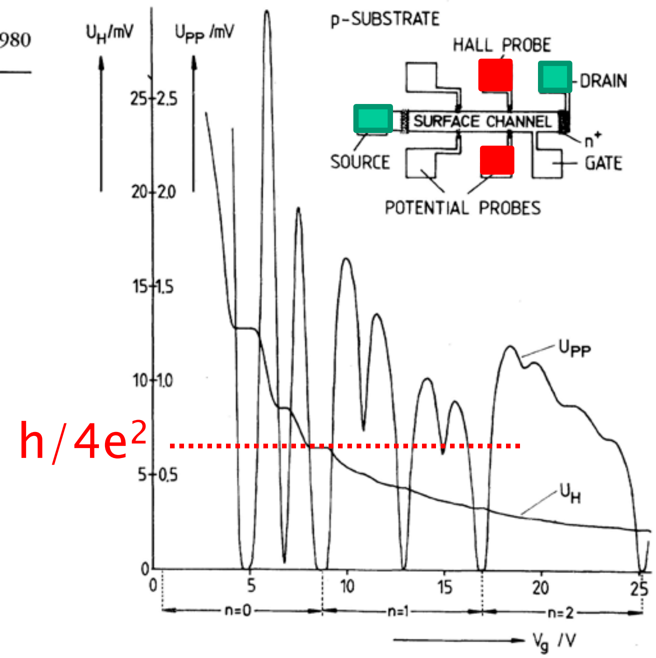


FIG. 1. Recordings of the Hall voltage U_H, and the voltage drop between the potential probes, U_{pp}, as a function of the gate voltage V_g at $T = 1.5$ K. The constant magnetic field (B) is 18 T and the source drain current, I, is 1 μA. The inset shows a top view of the device with a length of $L = 400$ μm, a width of $W = 50$ μm, and a distance between the potential probes of $L_{pp} = 130$ μm.

$$R_{xy} = h/ie^2 \text{ for filling factor } \nu \sim i$$

The Nobel Prize in Physics 1985
Klaus von Klitzing

The Nobel Prize in Physics 1985
Nobel Prize Award Ceremony
Klaus von Klitzing

Klaus von Klitzing

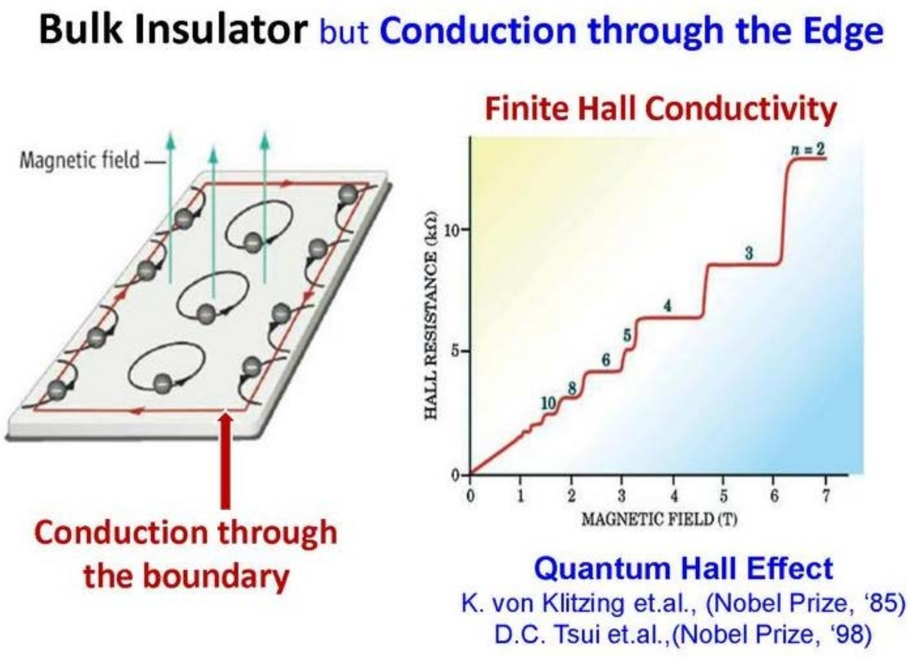
The Nobel Prize in Physics 1985 was awarded to Klaus von Klitzing *"for the discovery of the quantized Hall effect"*.

Quantum Hall systems are examples of **conducting insulators**

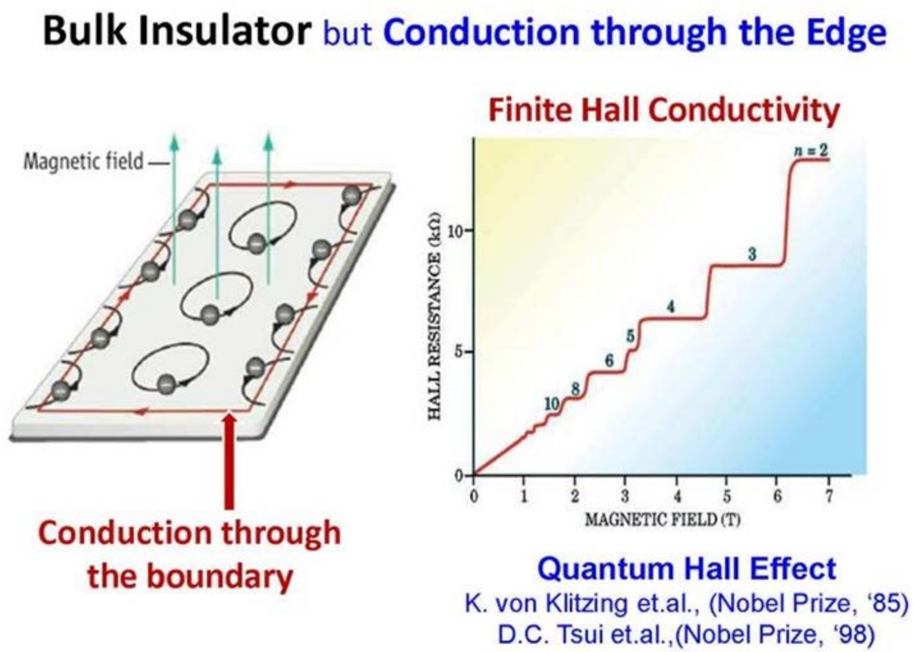
Magnetic quantization creates a gap in the bulk of the 2D system

At the same time, there are gapless chiral edge states

- *Quantized Hall resistances are “Topological quantum numbers”*

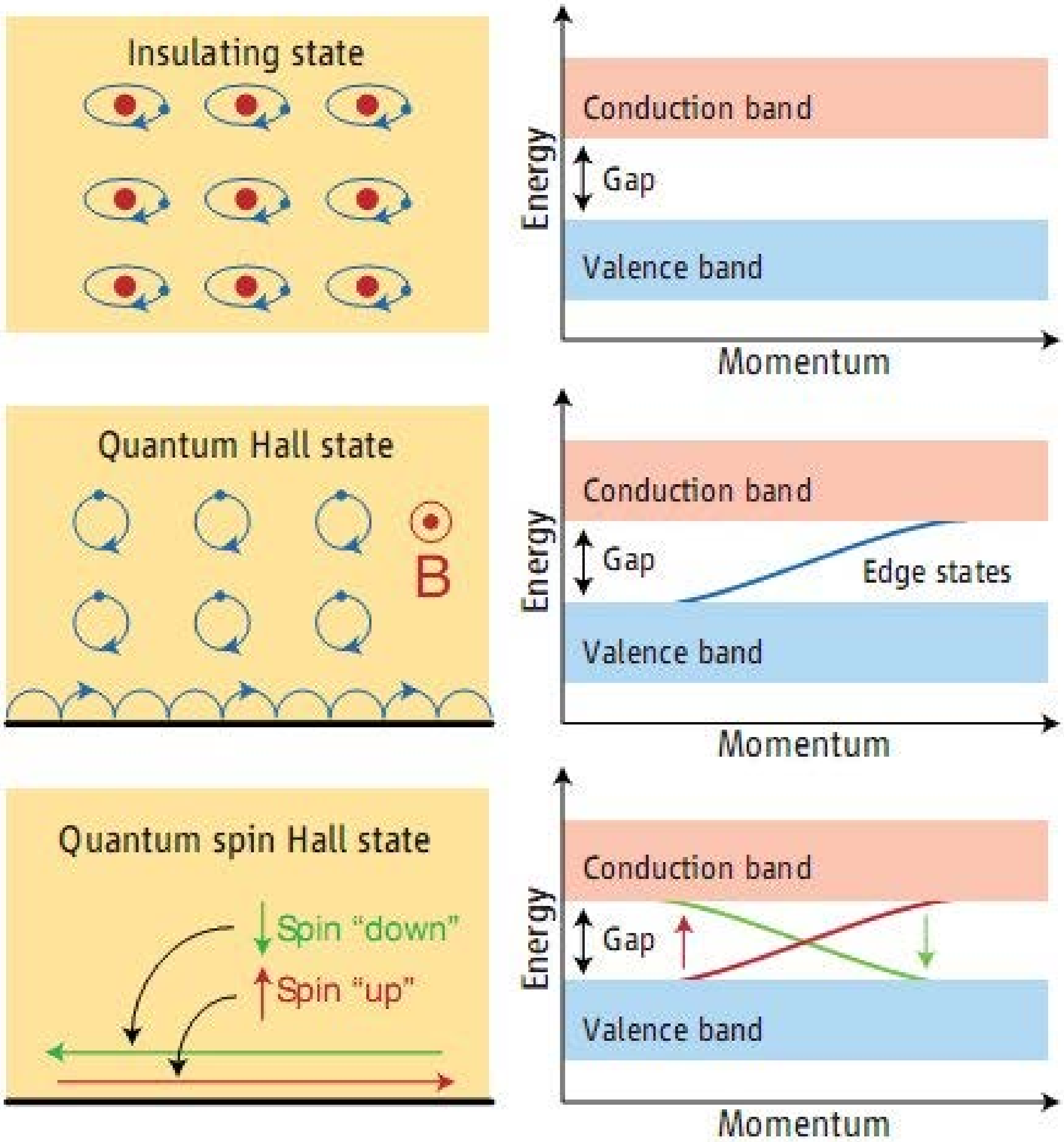


Recent development



•QHE is **a topologically ordered phase** (rather than a broken symmetry phase) because the quantized Hall conductance is a topological invariant.
•A material that behaves as an insulator in its interior while permitting the movement of charges on its surface is a topological insulator
•QHE is the prototype for **topological insulators**

Some examples of insulators



Band insulator

Quantum Hall effect:
Topological insulator

QSHE:
Topological insulator (w/
Z-2 topological order)
(strong spin-orbit interaction)

- Kane & Mele

This talk:

an unusual low-B zero-resistance state in the 2D electron system.

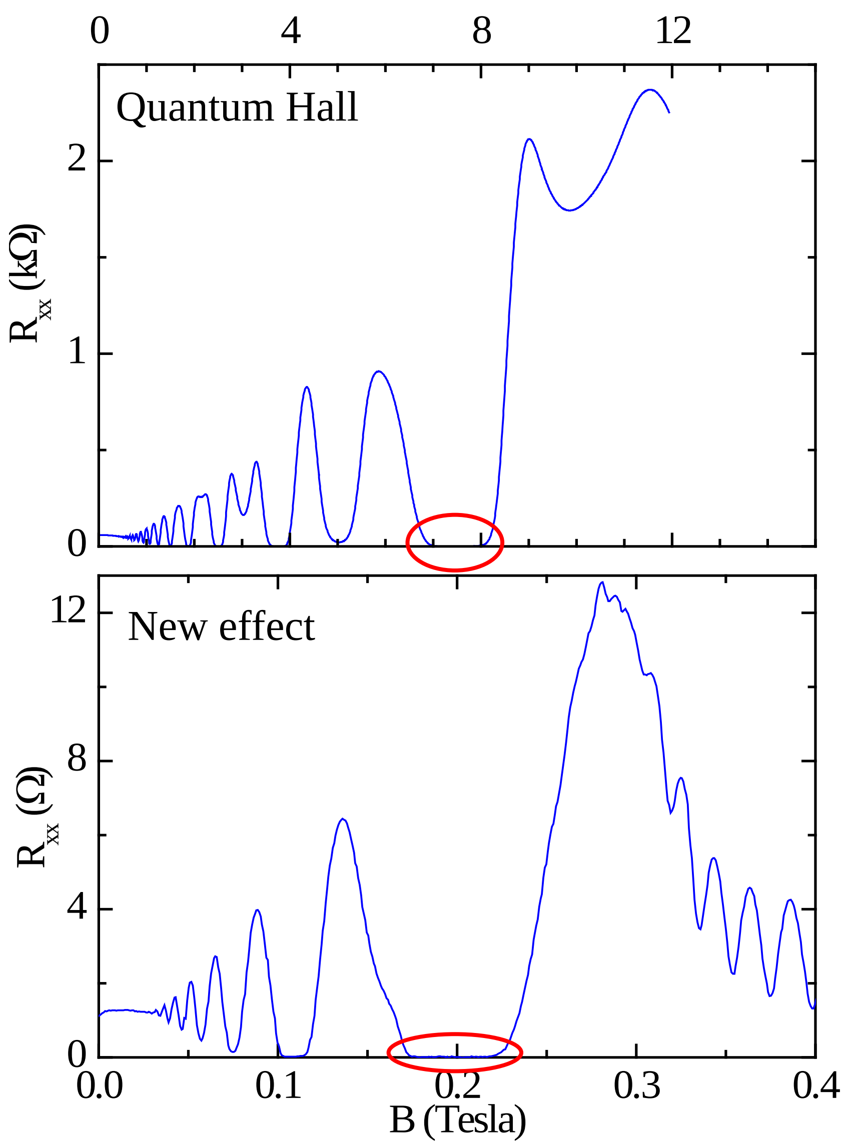
Like the QHE zero-resistance state, this radiation-induced zero-resistance state is an example of a **conducting insulator** at finite B!

i.e., $R_{xx} \rightarrow 0$ and $\sigma_{xx} \rightarrow 0$ at the same time!

But, there is no Hall quantization.

Question:

Broken symmetry phase or topologically insulating phase?



R. G. Mani et al., Nature **420**, 646-650 (2002)

Zero-resistance states induced by electromagnetic-wave excitation in GaAs/AlGaAs heterostructures

Ramesh G. Mani*†, Jürgen H. Smet†, Klaus von Klitzing†, Venkatesh Narayanamurti*‡, William B. Johnson§ & Vladimir Umansky‖

** Gordon McKay Laboratory of Applied Science, Harvard University, 9 Oxford Street, Cambridge, Massachusetts 02138, USA*
† Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany
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§ Laboratory for Physical Sciences, University of Maryland, College Park, Maryland 20740, USA
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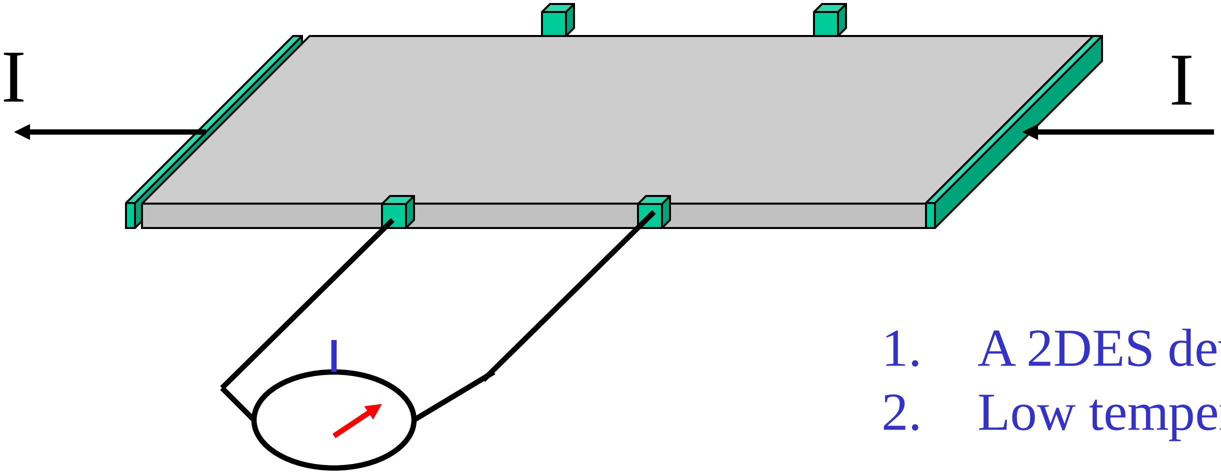
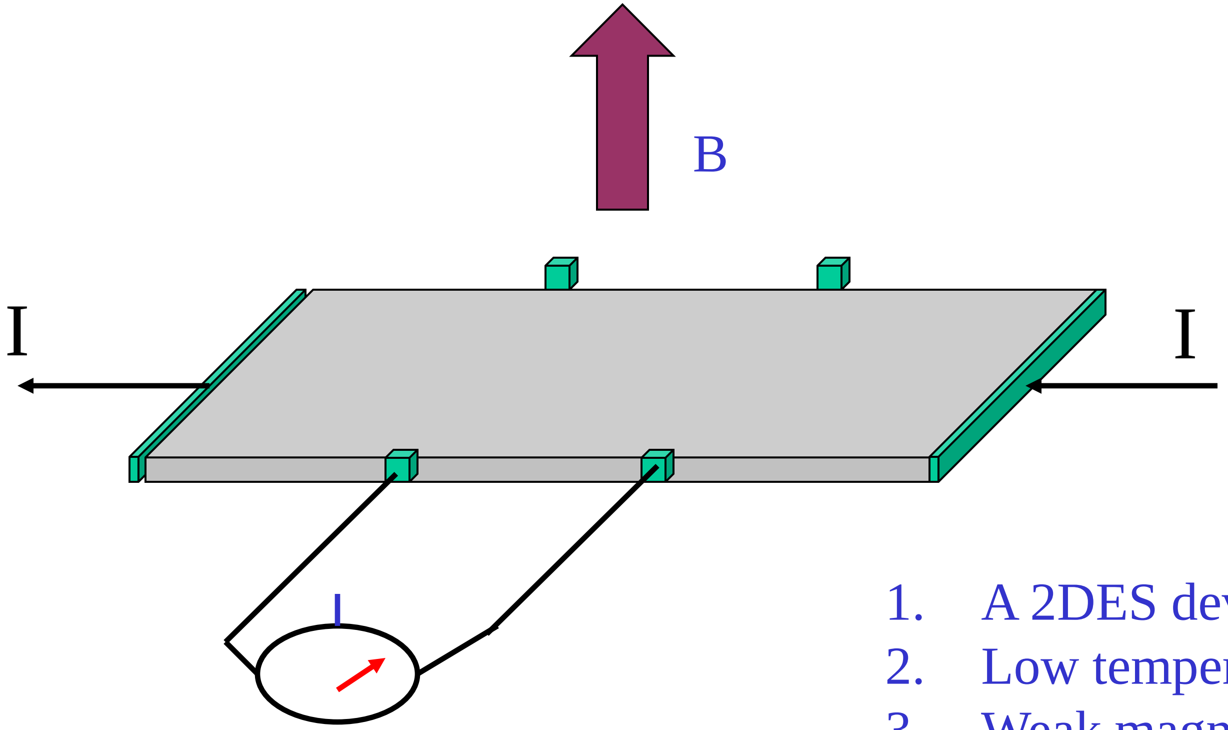
The observation of vanishing electrical resistance in condensed matter has led to the discovery of new phenomena such as, for example, superconductivity, where a zero-resistance state can be detected in a metal below a transition temperature T_c (ref. 1). More recently, quantum Hall effects were discovered from investigations of zero-resistance states at low temperatures and high magnetic fields in two-dimensional electron systems (2DESs)[2–4]. In quantum Hall systems and superconductors, zero-resistance states often coincide with the appearance of a gap in the energy spectrum[1,2,4]. Here we report the observation of zero-resistance states and energy gaps in a surprising setting[5]: ultrahigh-mobility GaAs/AlGaAs heterostructures that contain a 2DES exhibit vanishing diagonal resistance without Hall resistance quantization at low temperatures and low magnetic fields when the specimen is subjected to electromagnetic wave excitation. Zero-resistance-states occur about magnetic fields $B = 4/5B_f$ and $B = 4/9B_f$, where $B_f = 2\pi fm^*/e$, m^* is the electron mass, e is the electron charge, and f is the electromagnetic-wave frequency. Activated transport measurements on the resistance minima also indicate an energy gap at the Fermi level[6]. The results suggest an unexpected radiation-induced, electronic-state-transition in the GaAs/AlGaAs 2DES.

Conditions for realizing novel zero-resistance-states in the 2DES



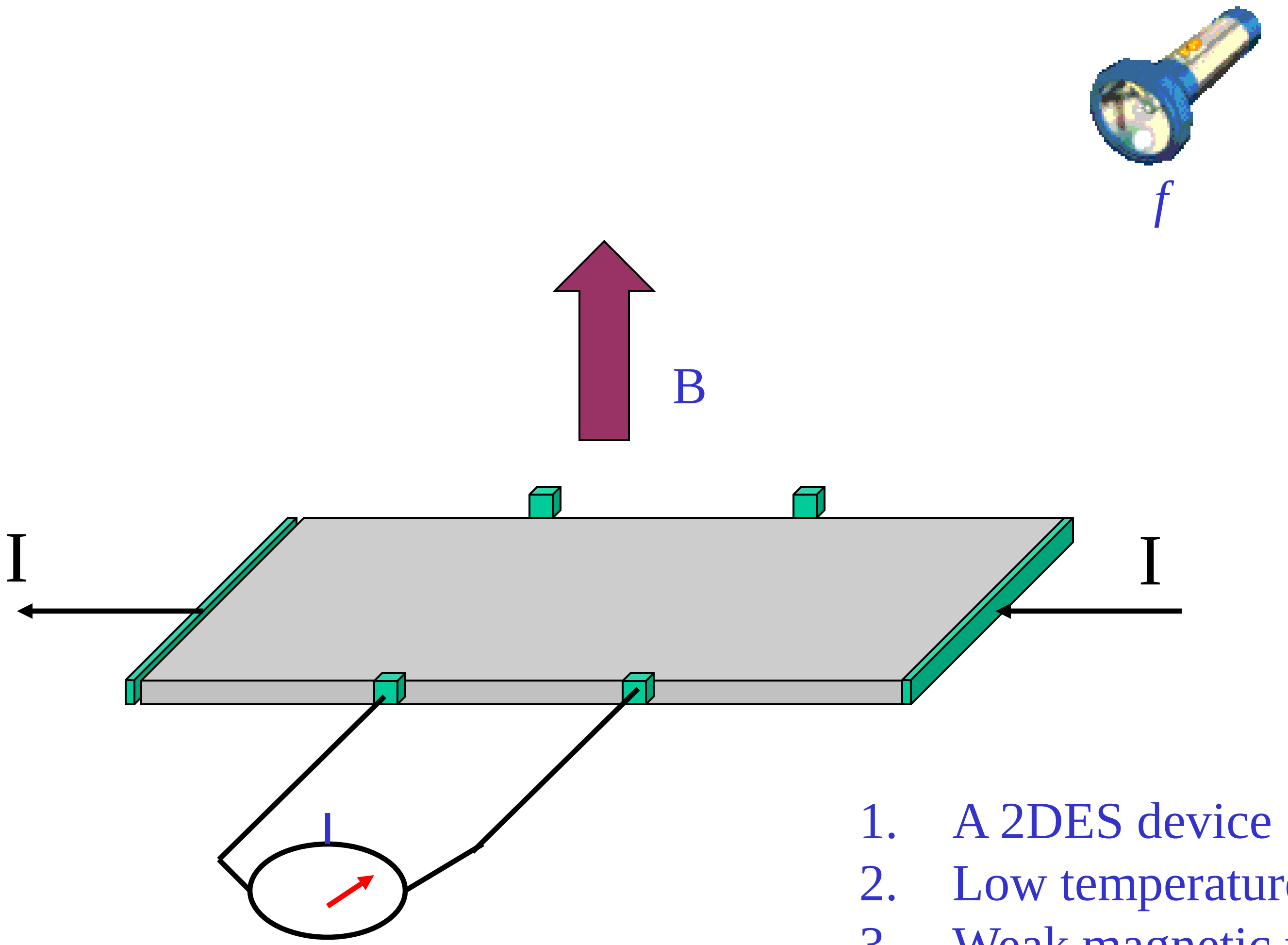
1. A 2DES device
2. Low temperature, ~ 1.5 K

Conditions for realizing novel zero-resistance-states in the 2DES



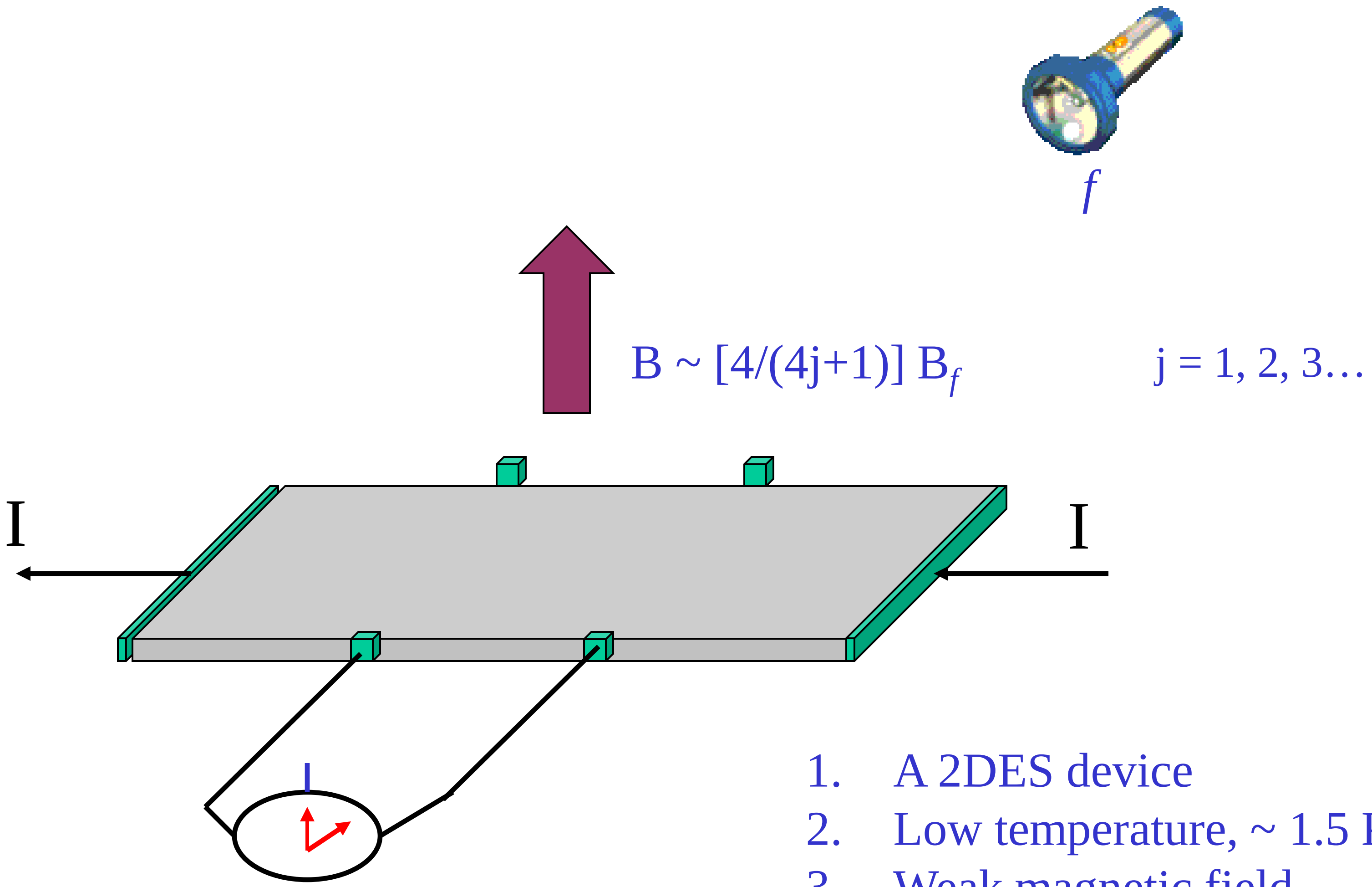
1. A 2DES device
2. Low temperature, ~ 1.5 K
3. Weak magnetic field

Conditions for realizing novel zero-resistance-states in the 2DES



1. A 2DES device
2. Low temperature, ~ 1.5 K
3. Weak magnetic field, B
4. Low energy photons, *f*

Conditions for realizing novel zero-resistance-states in the 2DES



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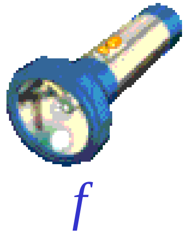
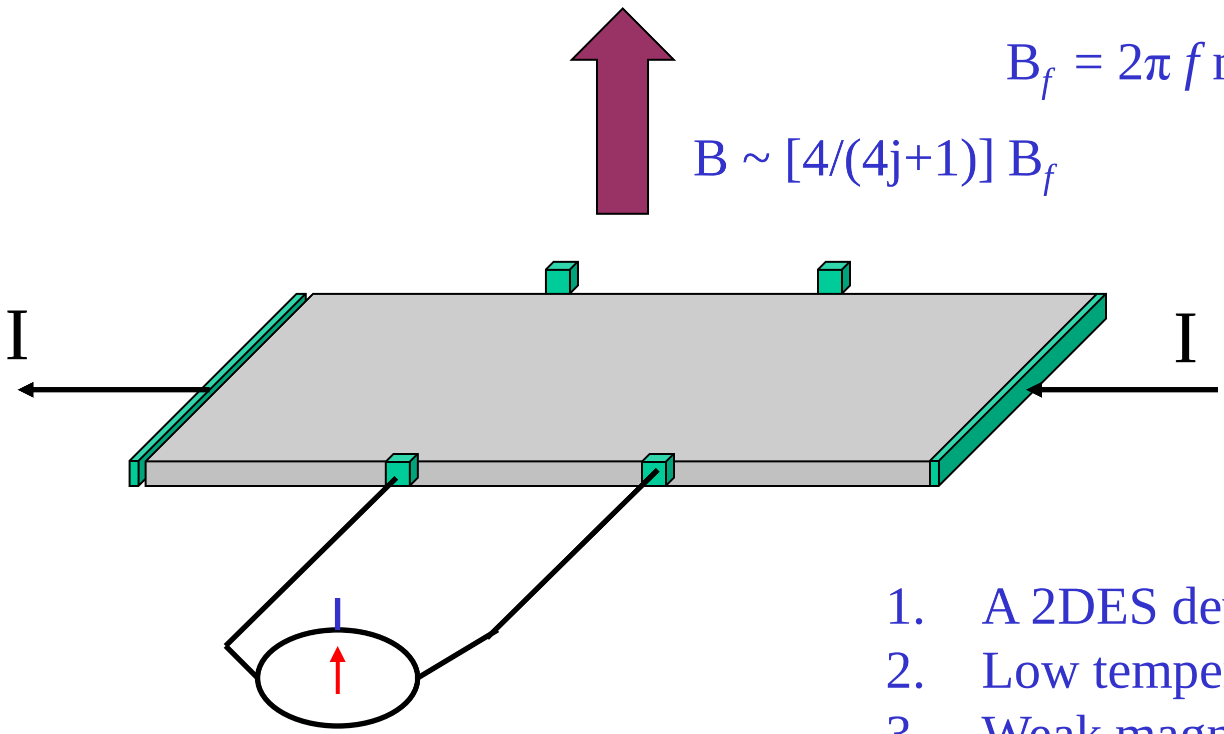


$B_f = 2\pi f m^*/e$

$B \sim [4/(4j+1)]\, B_f$ $\quad j = 1, 2, 3\ldots$



1. A 2DES device
2. Low temperature, ~ 1.5 K
3. Weak magnetic field
4. Low energy photons, *f*

activation energy (refs 2, 6; Fig. 3d).

Relevant scales include the cyclotron energy, $\hbar\omega_c$, the photon energy, hf, and the Landau level broadening $\pi k_B T_D$ (here T_D is the Dingle temperature). At the $B = 0.198$ T minimum (Fig. 1a), $\hbar\omega_c = 0.342$ meV is 4/5 of $hf = 0.428$ meV at 103.5 GHz, and the Hall effect implies a filling factor of ~63. The transport mean free path is 138 μm for $\mu = 1.5 \times 10^7\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$. The transport life-

$(B/B_f)^{-1} = 3/2$. The B^{-1} periodicity observed in the resistance, and the symmetry at $(B/B_f)^{-1} = 3/2$, suggest that the physical energy surplus/deficit, Δ, ought to vanish at $(B/B_f)^{-1} = 3/2$ in this situation. The construction of Δ from Δ' (Fig. 4b) follows this notion. Then, Fig. 4b indicates that Δ takes on maximal positive values at $(B/B_f)^{-1} = [4/(4j+1)]^{-1}$, favouring finite-$q$ excitons over the interval $[4/4j]^{-1} < (B/B_f)^{-1} < [4/(4j+2)]^{-1}$. The data (Fig. 1c) indicate that radiation reduces R_{xx} over corresponding intervals.

When $\Delta > 0$, electron pairing by exciton exchange can occur as in Fig. 4c (ref. 25). Here, the scattering of an electron from $\mathbf{k_1}$ to $\mathbf{k_2} = \mathbf{k_1} + \mathbf{q}$ provides wavevector for the exciton, and facilitates access to the finite-q portion of the dispersion relation. Such correlated scattering could produce a pairing instability near the Fermi surface[23–27], resulting in a spectral gap. As radiation facilitates q-carrying excitons, a spectral gap can occur only under illumination. The periodic (in B^{-1}) reappearance of q-carrying excitons leads to the periodic reoccurrence of electron pairing, and vanishing resistance. In contrast, when $\Delta < 0$, a local energy deficit for exciton creation increases the electron inelastic-scattering cross-section, producing radiation-enhanced resistance over corresponding intervals. Thus, this interpretation suggests that excitons induce a pairing instability[23–26] in the 2DES system around $B = [4/(4j+1)]B_f$, which leads to a spectral gap, activated transport[6] and zero-resistance-states[3], while the lack of phase coherence prevents the realization of typical superconductivity[1,28]. These results complement studies of exciton condensation in the quantum Hall regime[29,30], and studies of exciton ordering and transport in coupled quantum wells[31,32]. □

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Ramesh G. Mani*†, Jürgen H. Smet†, Klaus von Klitzing†, Venkatesh Narayanamurti*‡, William B. Johnson§ & Vladimir Umansky‖

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VOLUME 90, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2003

Evidence for a New Dissipationless Effect in 2D Electronic Transport

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L. N. Pfeiffer and K. W. West
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(Received 6 September 2002; published 30 January 2003)

In an ultraclean 2D electron system (2DES) subjected to crossed millimeterwave (30–150 GHz) and weak ($B < 2$ kG) magnetic fields, a series of apparently dissipationless states emerges as the system is detuned from cyclotron resonances. Such states are characterized by an exponentially vanishing low-temperature diagonal resistance and a classical Hall resistance. The activation energies associated with such states exceed the Landau level spacing by an order of magnitude. Our findings are likely indicative of a collective ground state previously unknown for 2DES.

Some names in the field:

Experiment:

- Mani, Ramanayaka, Ye
- Zudov & Du, Hatke & Zudov, Yang
- Studenikin et al.,
- Dorozhkin, Smet, vK; Andreev
- Weidmann et al.
- Konstantinov & Kono

Crystal growers:

- Umansky, Wegscheider, Pfeiffer & West

Theory:

- Ryzhii
- Durst, Sachdev, Read, Girvin,
- Andreev, Aleiner & Millis
- Shikin
- Vavilov & Aleiner
- Dmitriev, Mirlin & Polyakov; Khodas
- Inarrea & Platero
- Lei & Liu
- Mikhailov
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Outline

- Experimental details

- The basic zero-resistance effect
- Tilt field experiment: 2D orbital effect
- Temperature dependence: Activated transport
- Examine overlap of zero-resistance states and quantum Hall effect
- ZRS analogs in other 2D systems: e^- on liquid helium

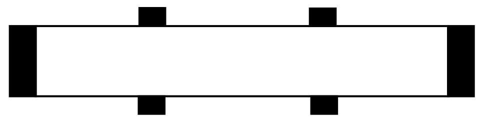
- Review of theories

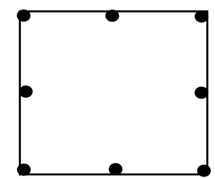
- Conclusion

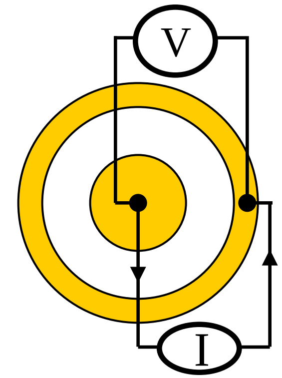
Experiment

Samples:

- GaAs/AlGaAs heterostructures with $2.4 \times 10^{11} < n < 3 \times 10^{11} cm^{-2}$ and mobility $7 \times 10^6 < \mu < 20 \times 10^6\ cm^2/Vs$.
- High field condition: $\omega_C \tau > 1$ for $B > 1$ mT!!
- Mean free path for electrons @ 1.5K: up to 200 microns.







Temperature:

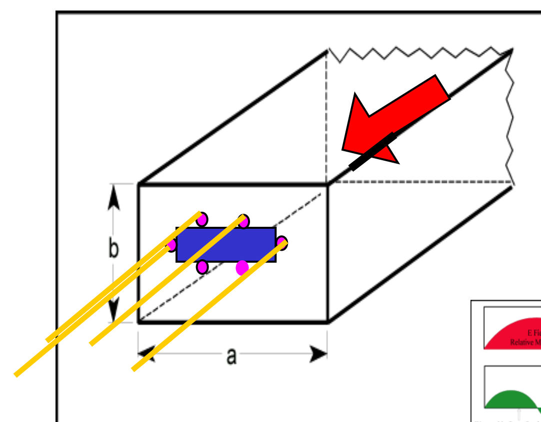
- $0.5 < T < 4.2$ K

Radiation:

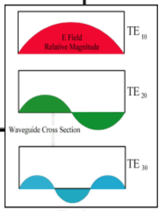
Rectangular waveguide:

- Linearly polarized microwaves
- Power level ≤ 1mW over 135 mm^2

Circular waveguide: next talk



. The Rectangular Waveguide



. TE modes

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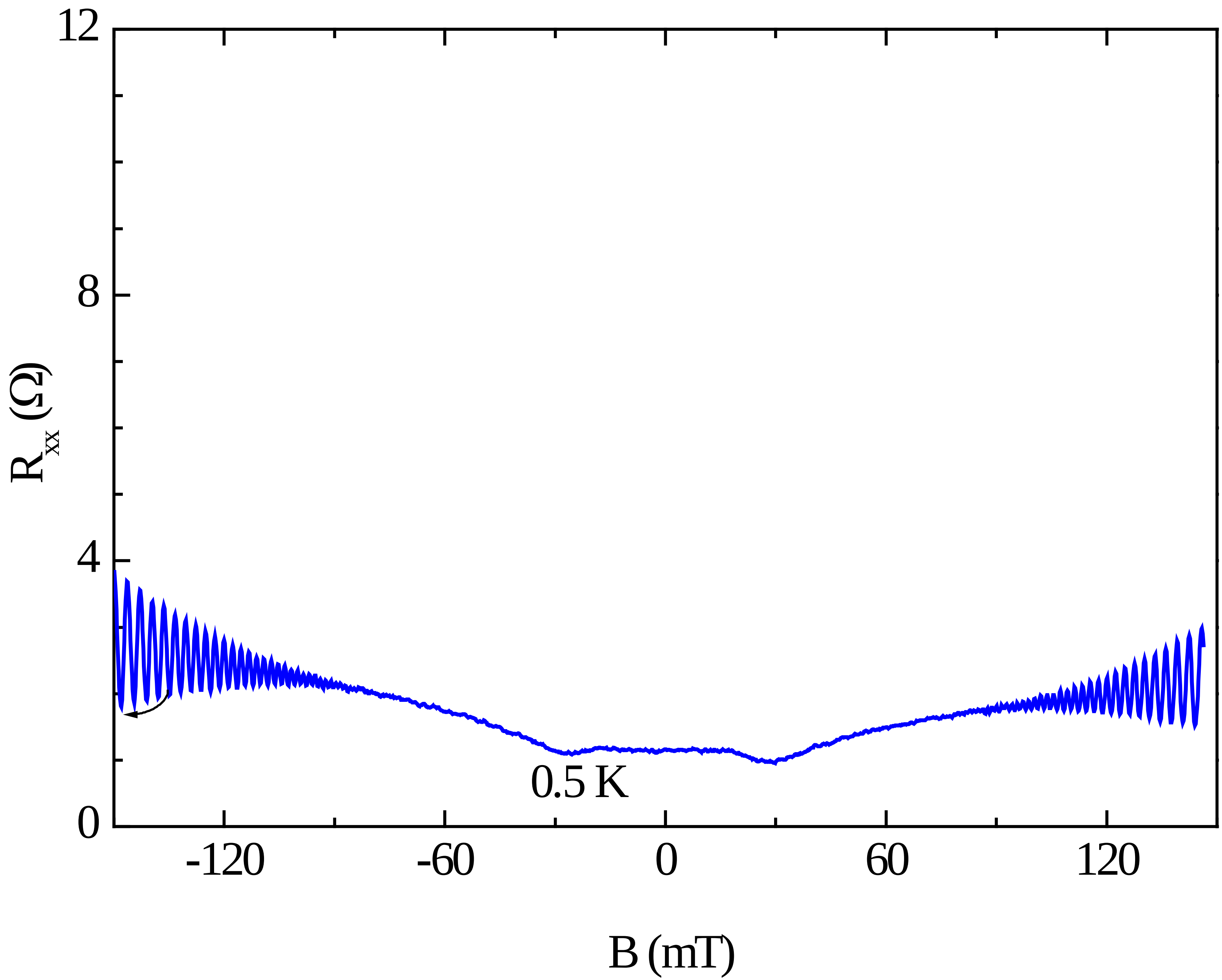
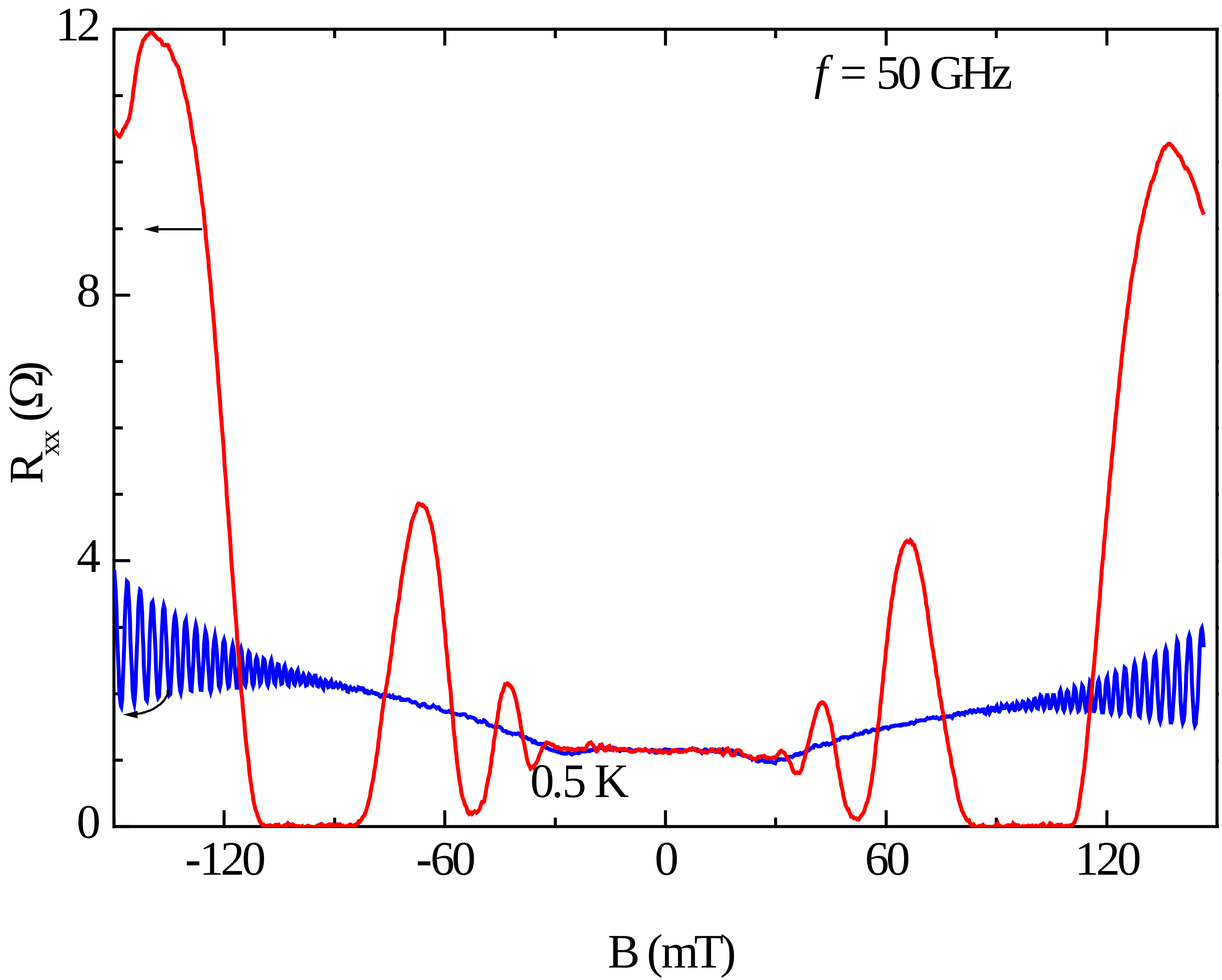
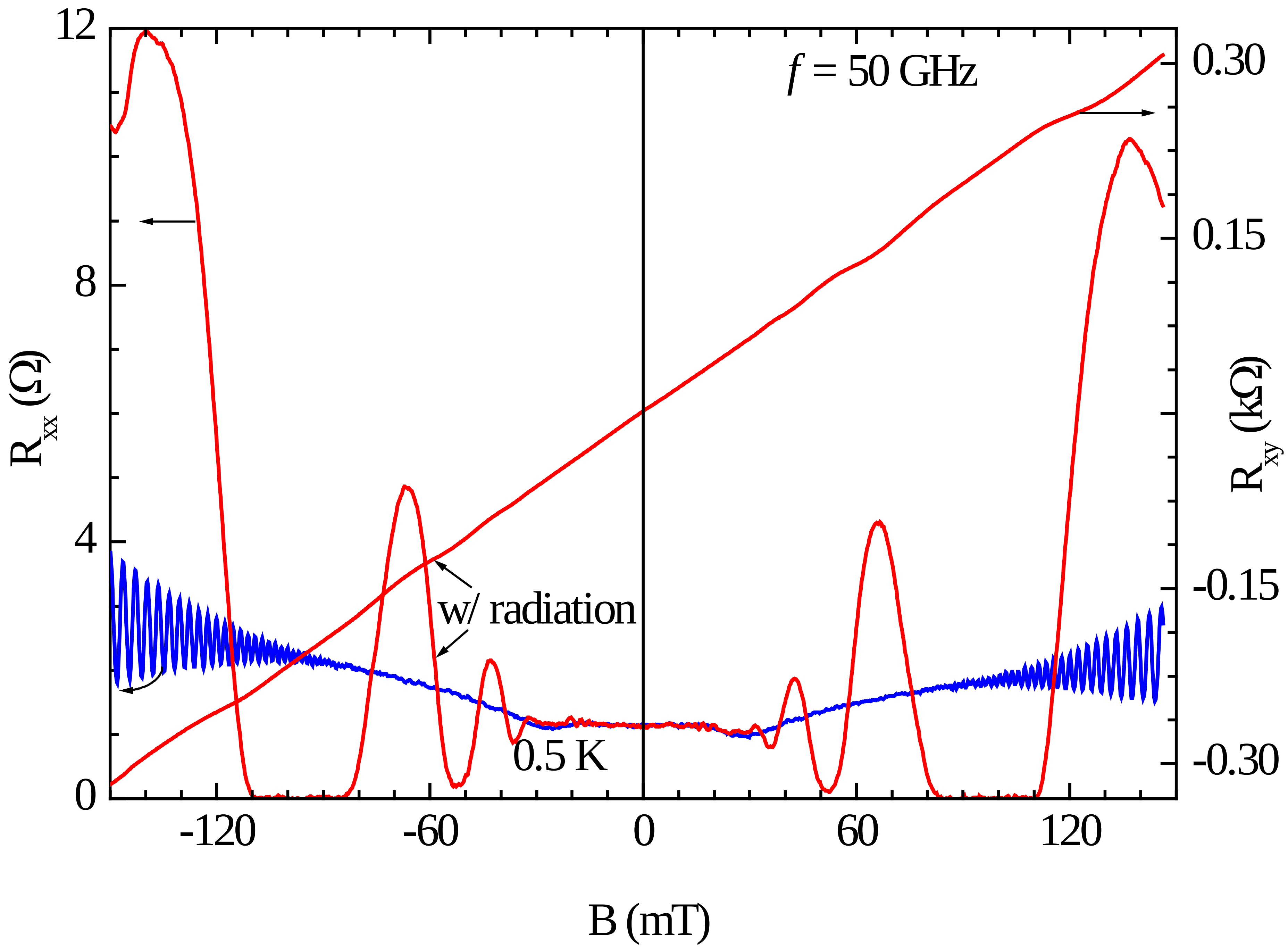


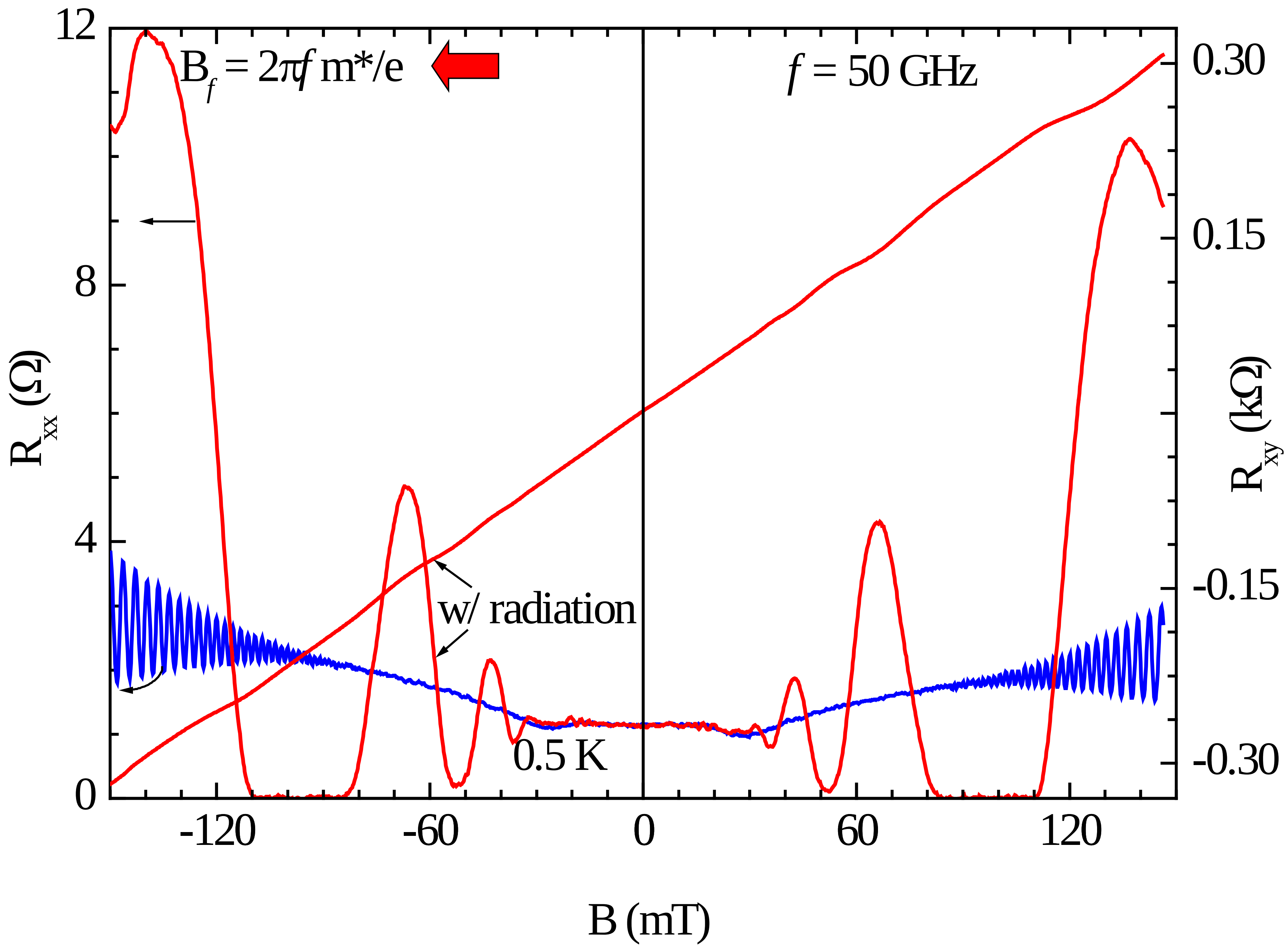
12
8
4
0
R_{xx} (Ω)
0.5 K
-120
-60
0
60
120
B (mT)



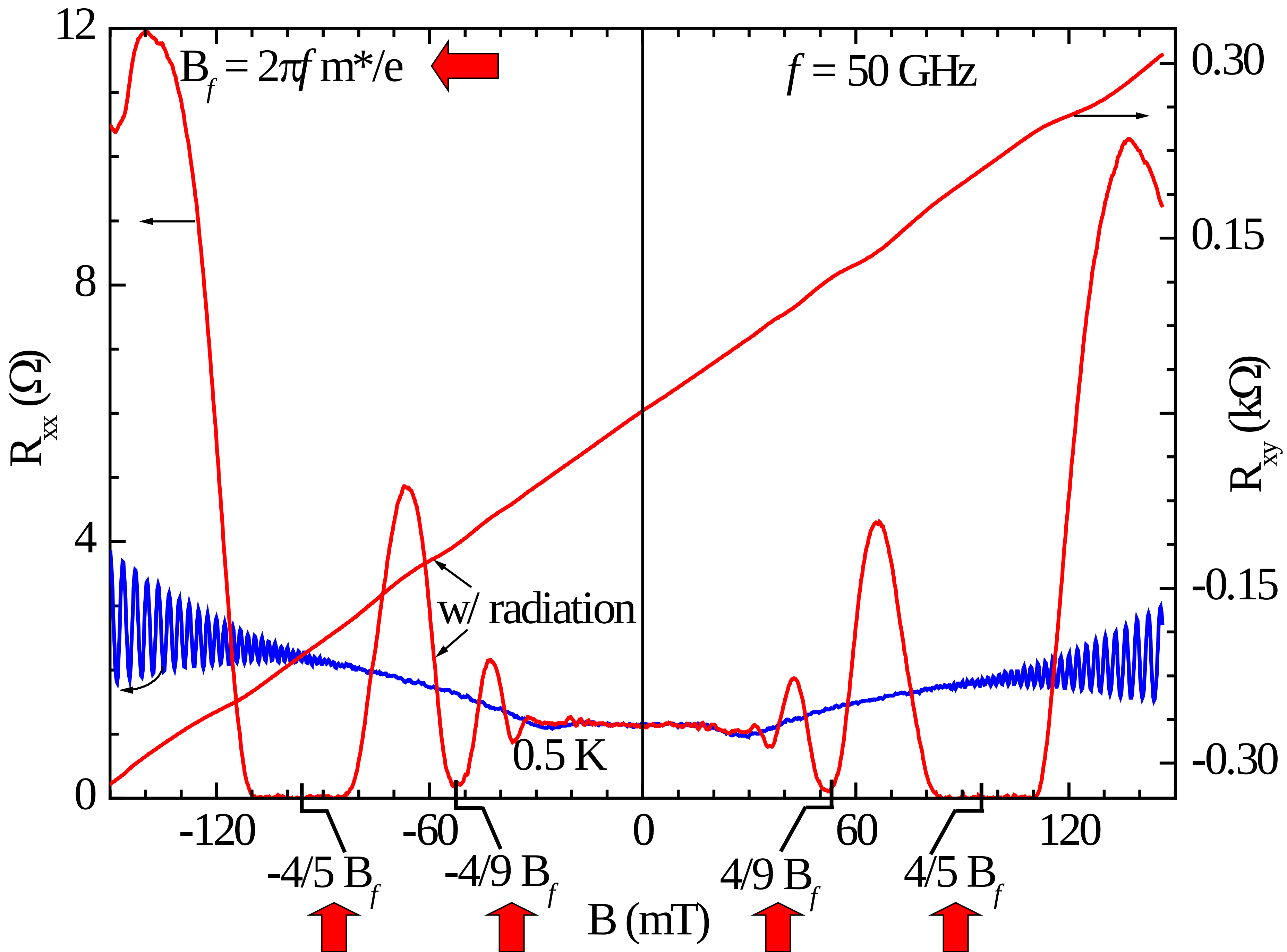
12
8
4
0
-120
-60
0
60
120
R_{xx} (Ω)
B (mT)
f = 50 GHz
0.5 K



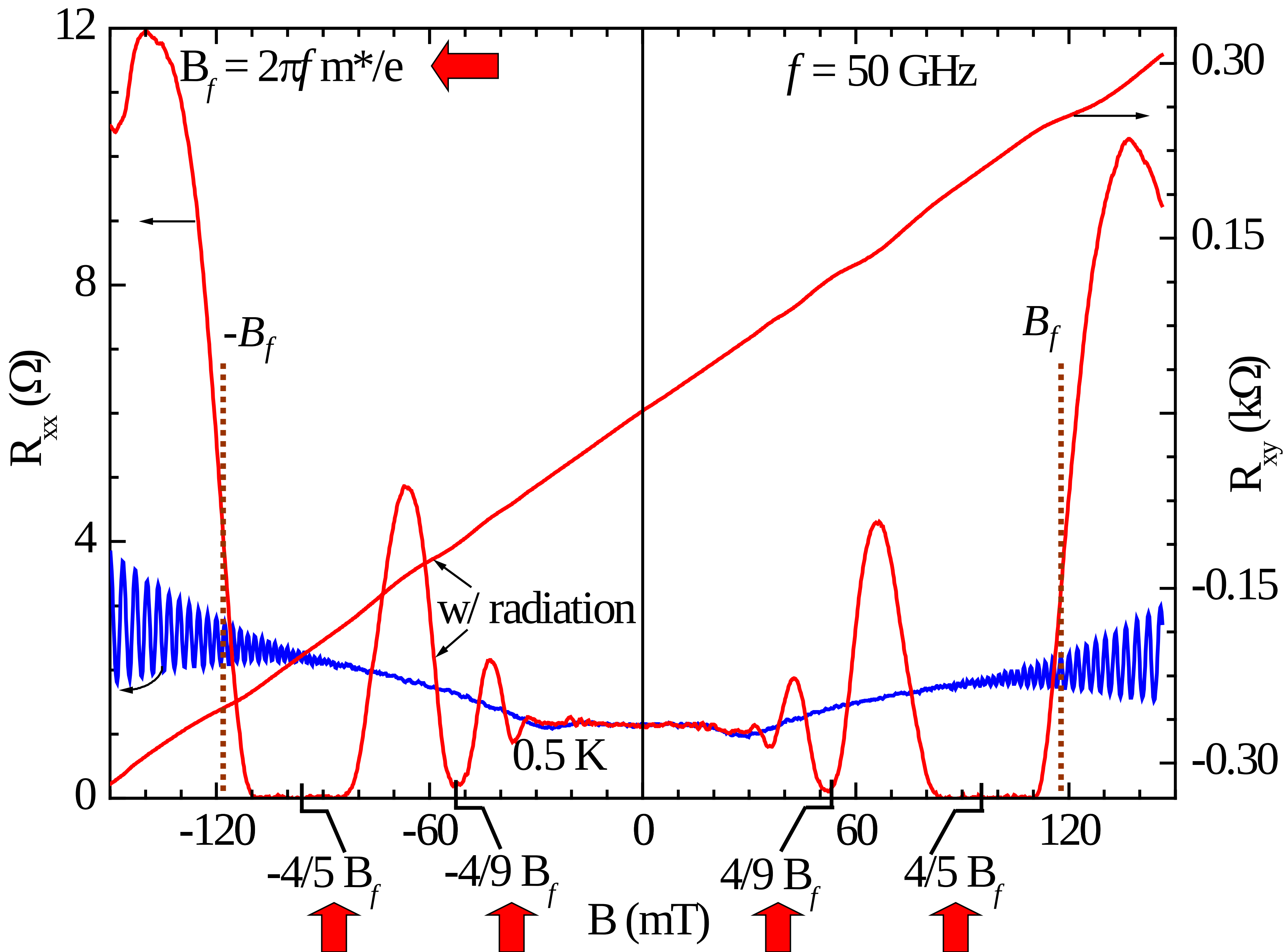
12
8
4
0
0.30
0.15
-0.15
-0.30
-120
-60
0
60
120
f = 50 GHz
w/ radiation
0.5 K
R_{xx} (Ω)
R_{xy} (kΩ)
B (mT)



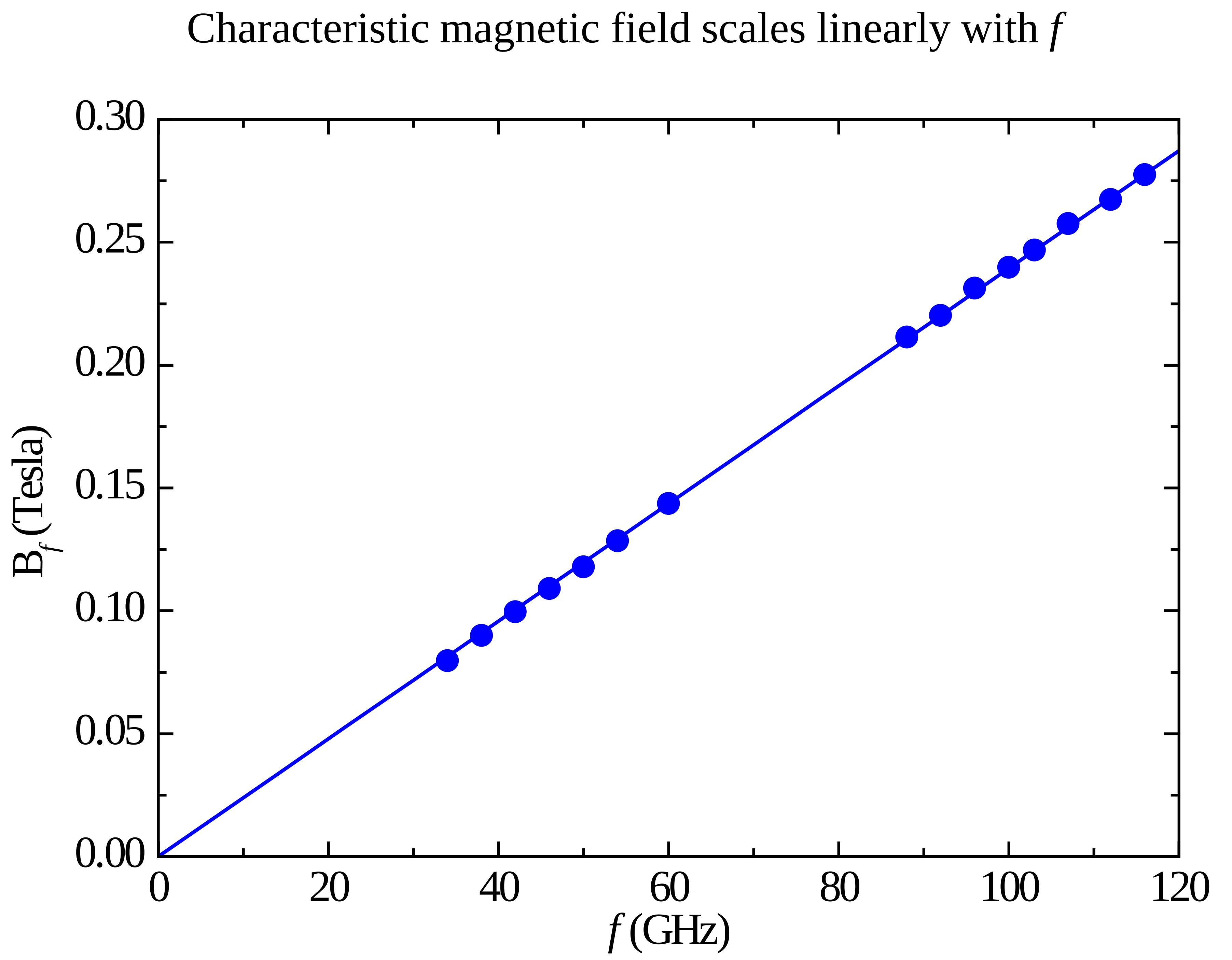
12
8
4
0
-120
-60
0
60
120
0.30
0.15
-0.15
-0.30
R_{xx} (Ω)
R_{xy} (kΩ)
B (mT)
$B_f = 2\pi f\, m^*/e$
f = 50 GHz
w/ radiation
0.5 K



12
8
4
0
0.30
0.15
-0.15
-0.30
$B_f = 2\pi f\, m^*/e$
f = 50 GHz
w/ radiation
0.5 K
R_{xx} (Ω)
R_{xy} (kΩ)
-120
-60
0
60
120
-4/5 B_f
-4/9 B_f
4/9 B_f
4/5 B_f
B (mT)

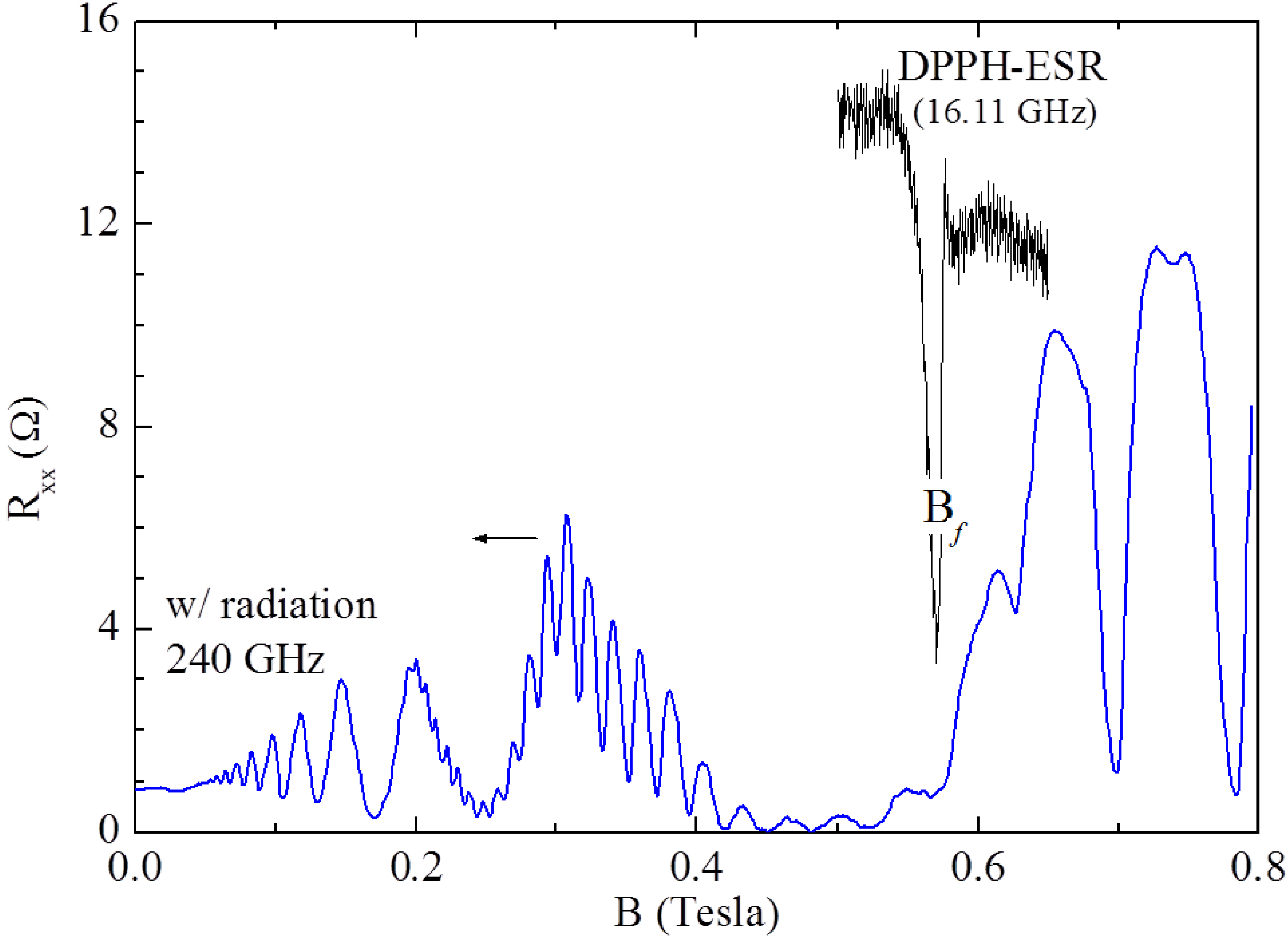


$B_f = 2\pi f\, m^*/e$
f = 50 GHz
$-B_f$
B_f
w/ radiation
0.5 K
R_{xx} (Ω)
R_{xy} (kΩ)
B (mT)
-4/5 B_f
-4/9 B_f
4/9 B_f
4/5 B_f
12
8
4
0
0.30
0.15
-0.15
-0.30
-120
-60
0
60
120

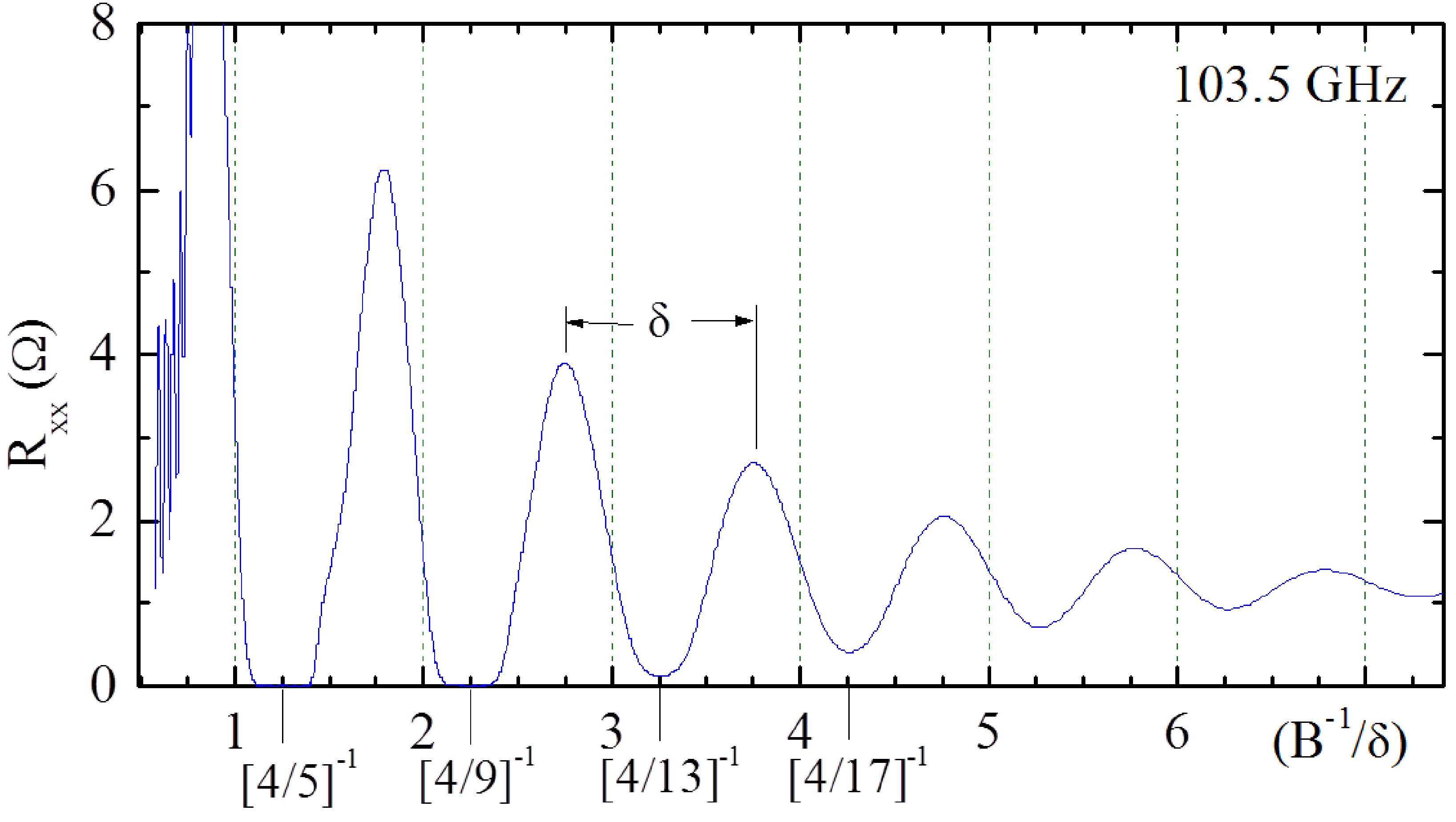


Characteristic magnetic field scales linearly with f
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
B_f (Tesla)
f (GHz)

Transport under photo-excitation at 240 GHz



Diagonal resistance R_{xx} vs. inverse magnetic field, B



- Oscillatory resistance nodes occur at integer values
- Extrema shifted by ¼ cycle
- $R_{xx} \sim -\sin(2\pi F/B)$

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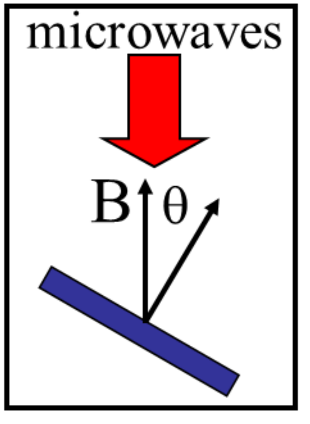
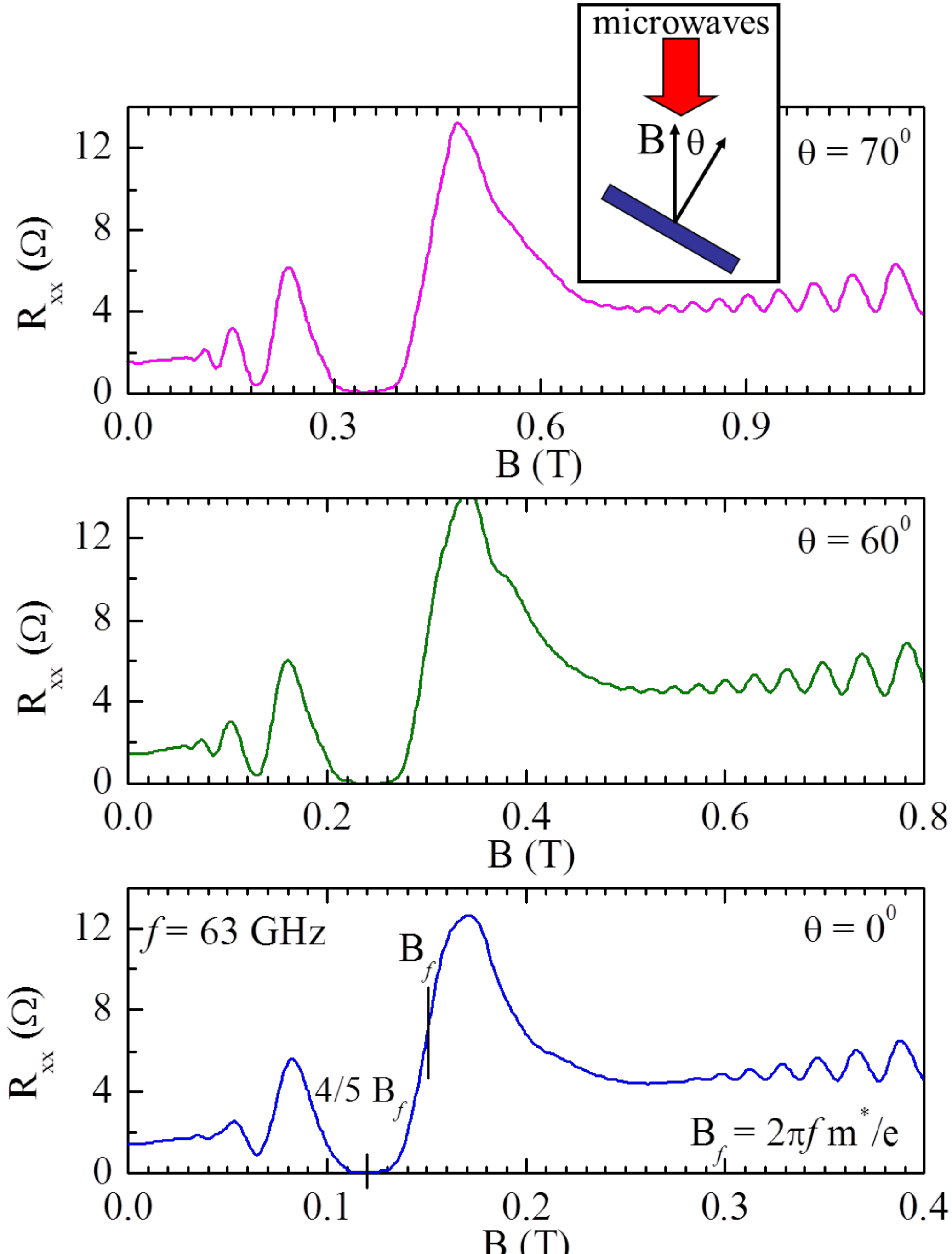
Is this a 2D orbital effect?

•Examine the effect of tilting the sample in the magnetic field.

→2D orbital effect should depend only on the ⊥ component of B

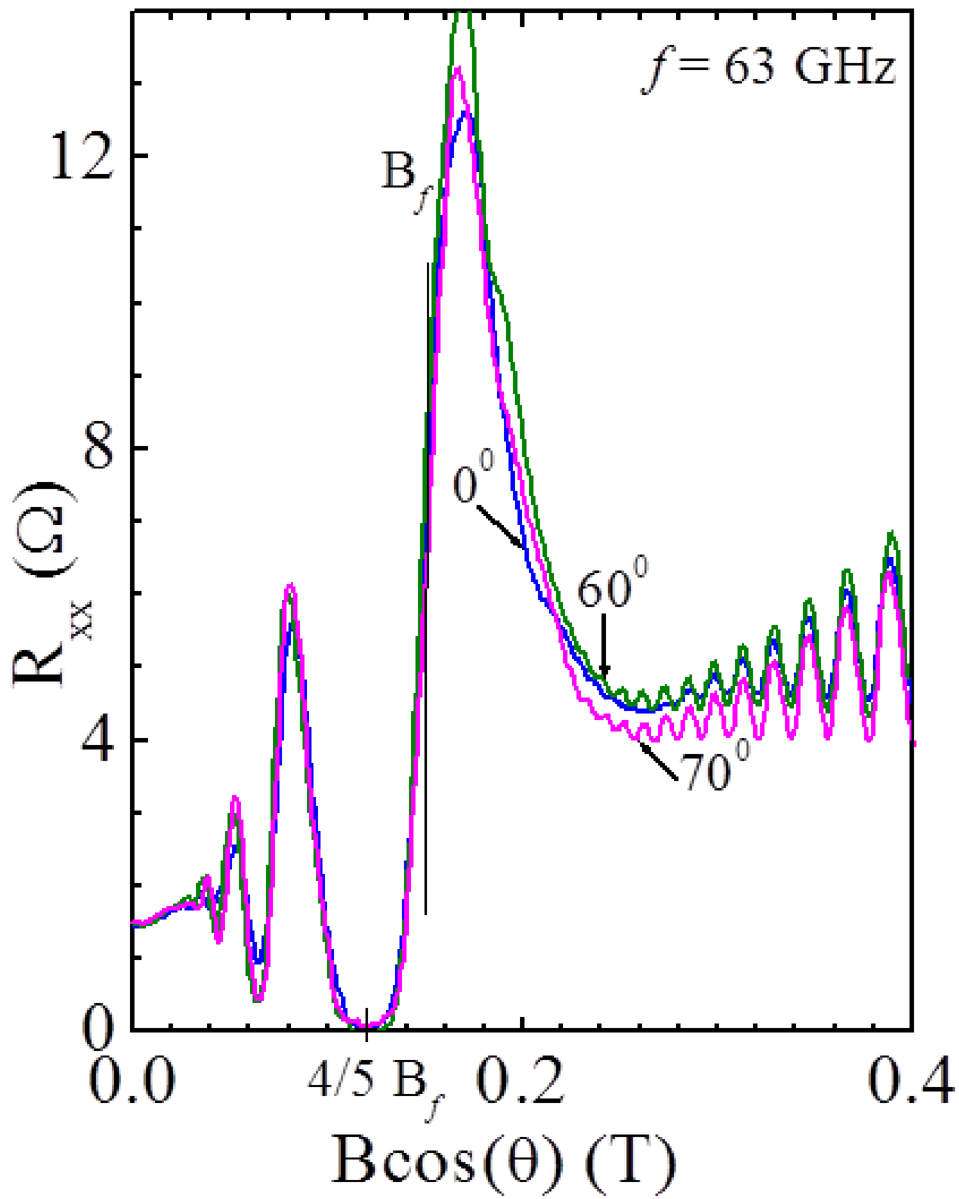


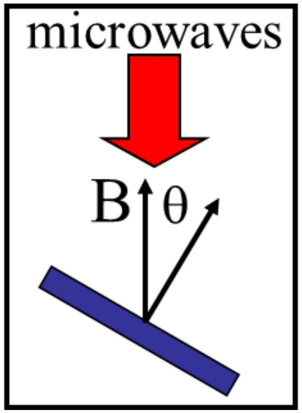


microwaves
B
θ
θ = 70^0
R_xx (Ω)
B (T)
θ = 60^0
R_xx (Ω)
B (T)
f = 63 GHz
B_f
4/5 B_f
θ = 0^0
B_f = 2πf m*/e
R_xx (Ω)
B (T)

Effect depends on $B_\perp$

→2D orbital effect





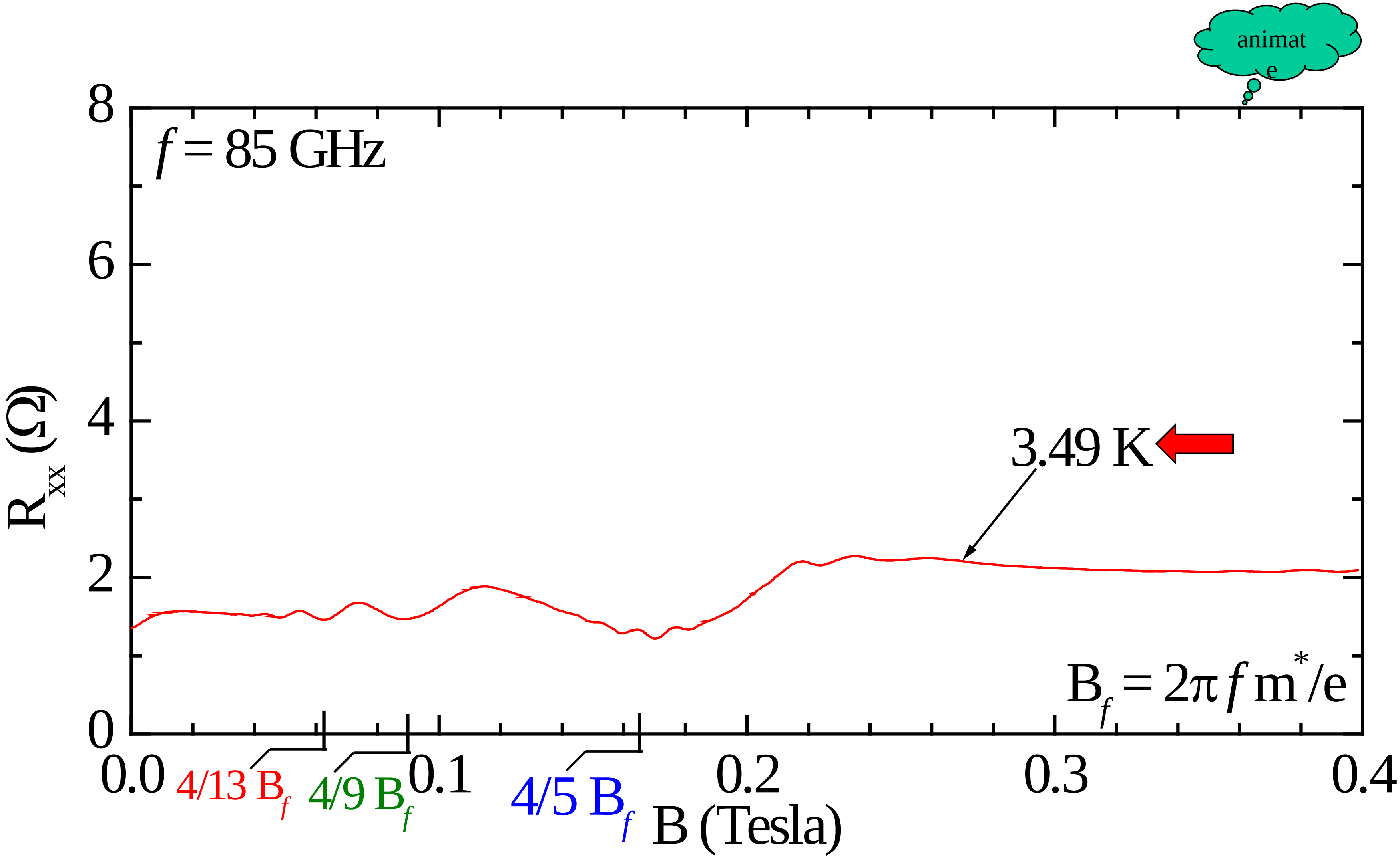
Outline

- Experimental details

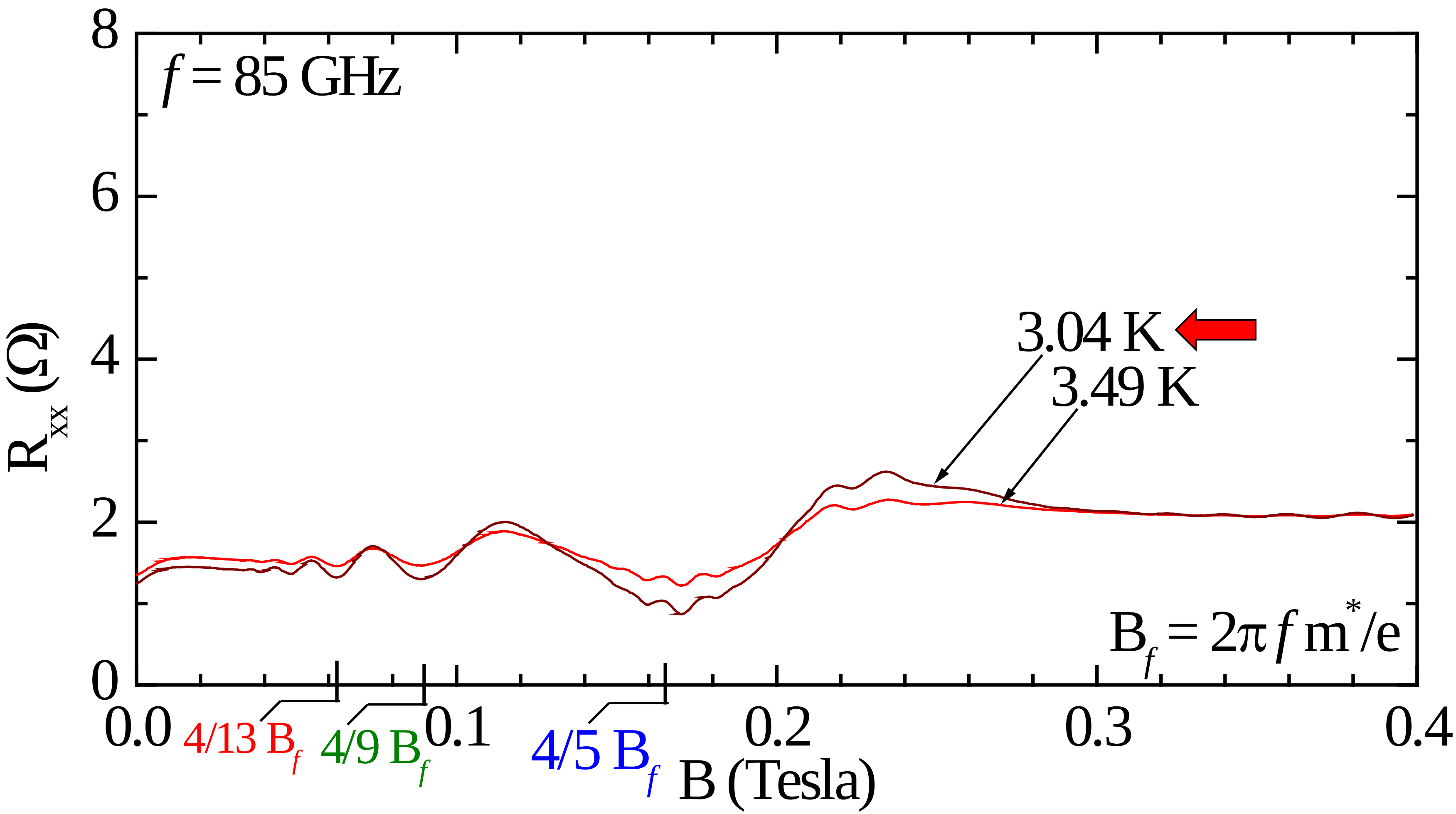
- The basic zero-resistance effect
- Tilt field experiment: 2D orbital effect
- **Temperature dependence: Activated transport**
- Study of overlap of zero-resistance states and quantum Hall effect
- ZRS in other 2D systems: e^- on liquid helium

- Review of theories

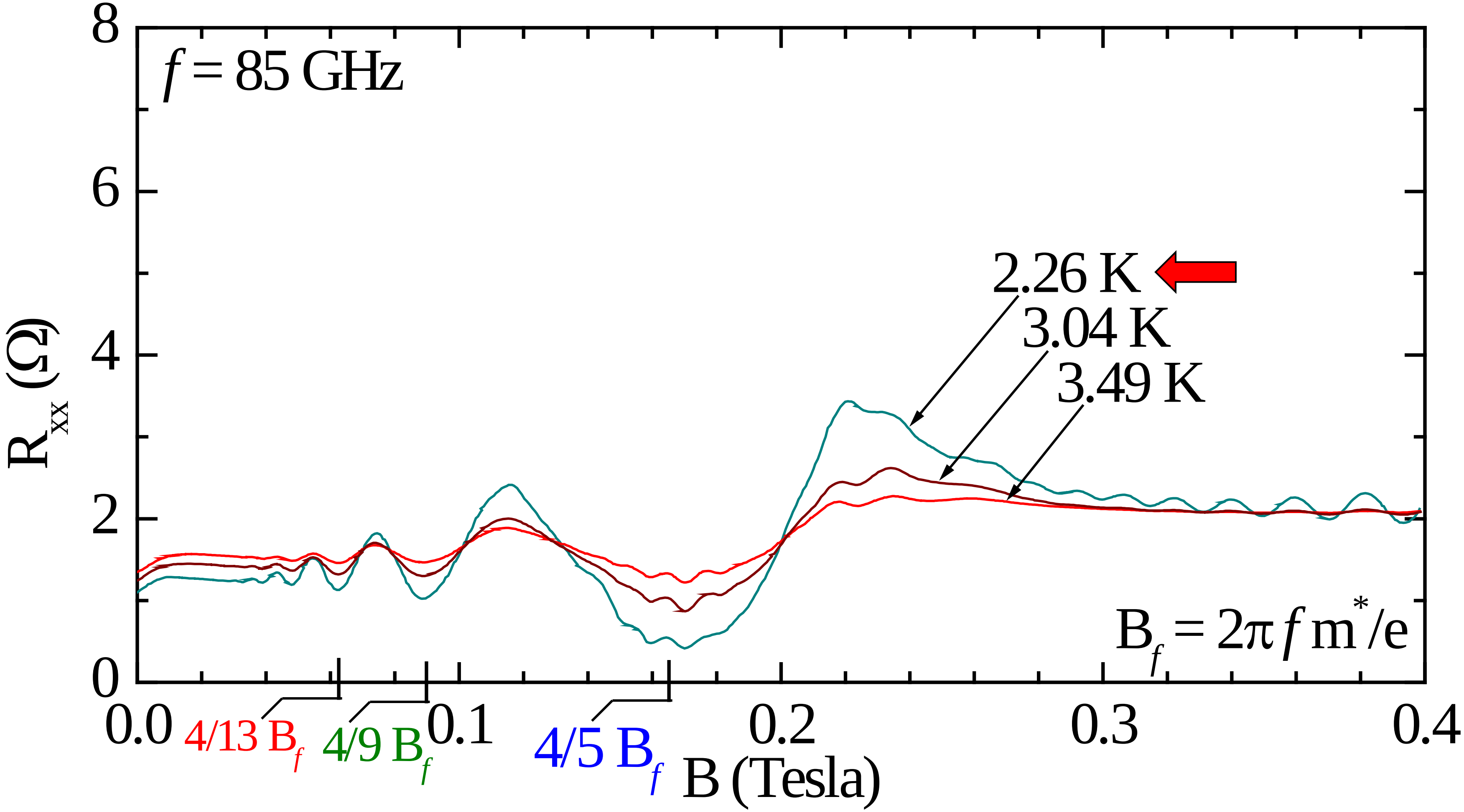
- Conclusion



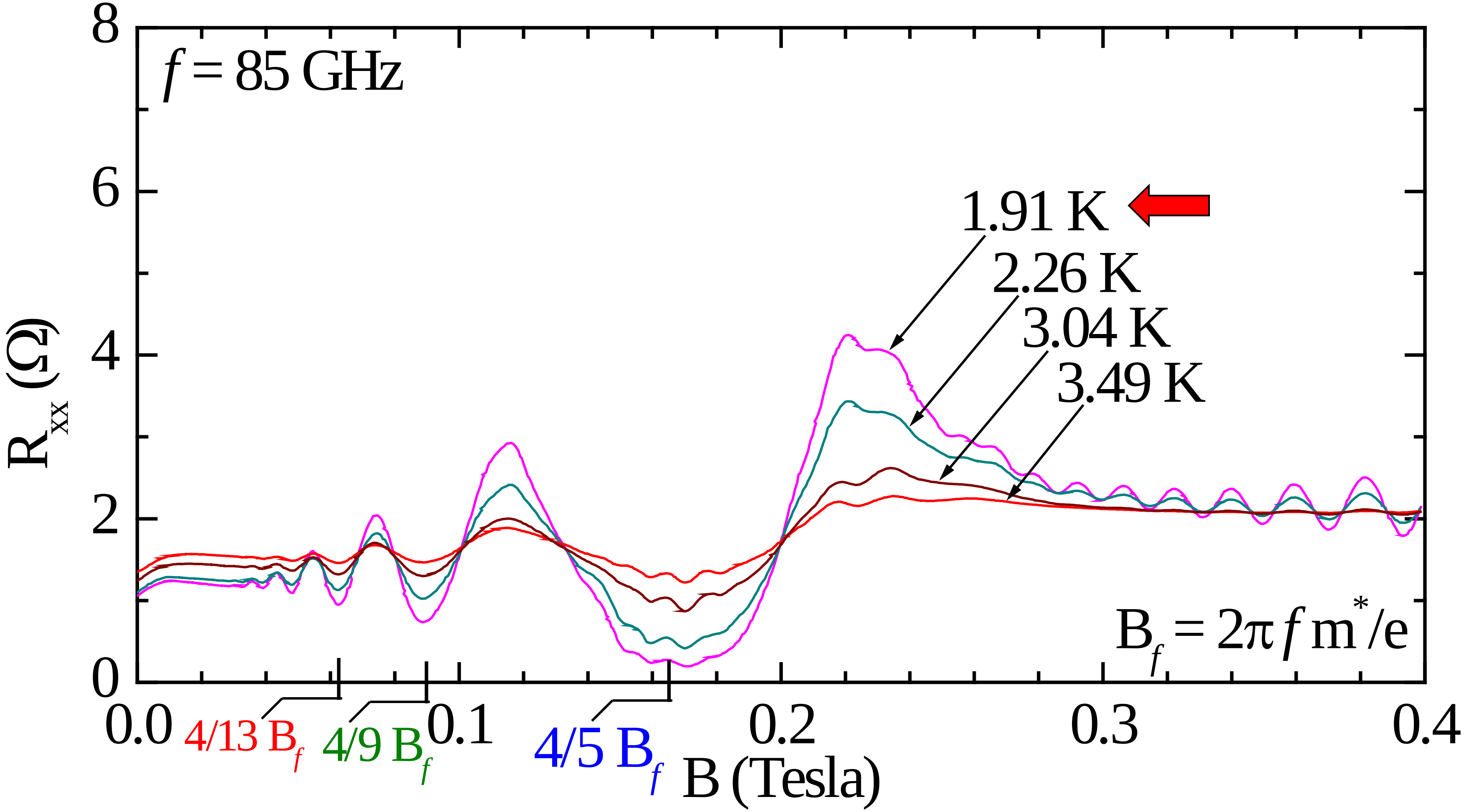
animat e
8
6
4
2
0
R_{xx} (Ω)
f = 85 GHz
3.49 K
$B_f = 2\pi f m^*/e$
0.0
0.1
0.2
0.3
0.4
4/13 B_f
4/9 B_f
4/5 B_f
B (Tesla)



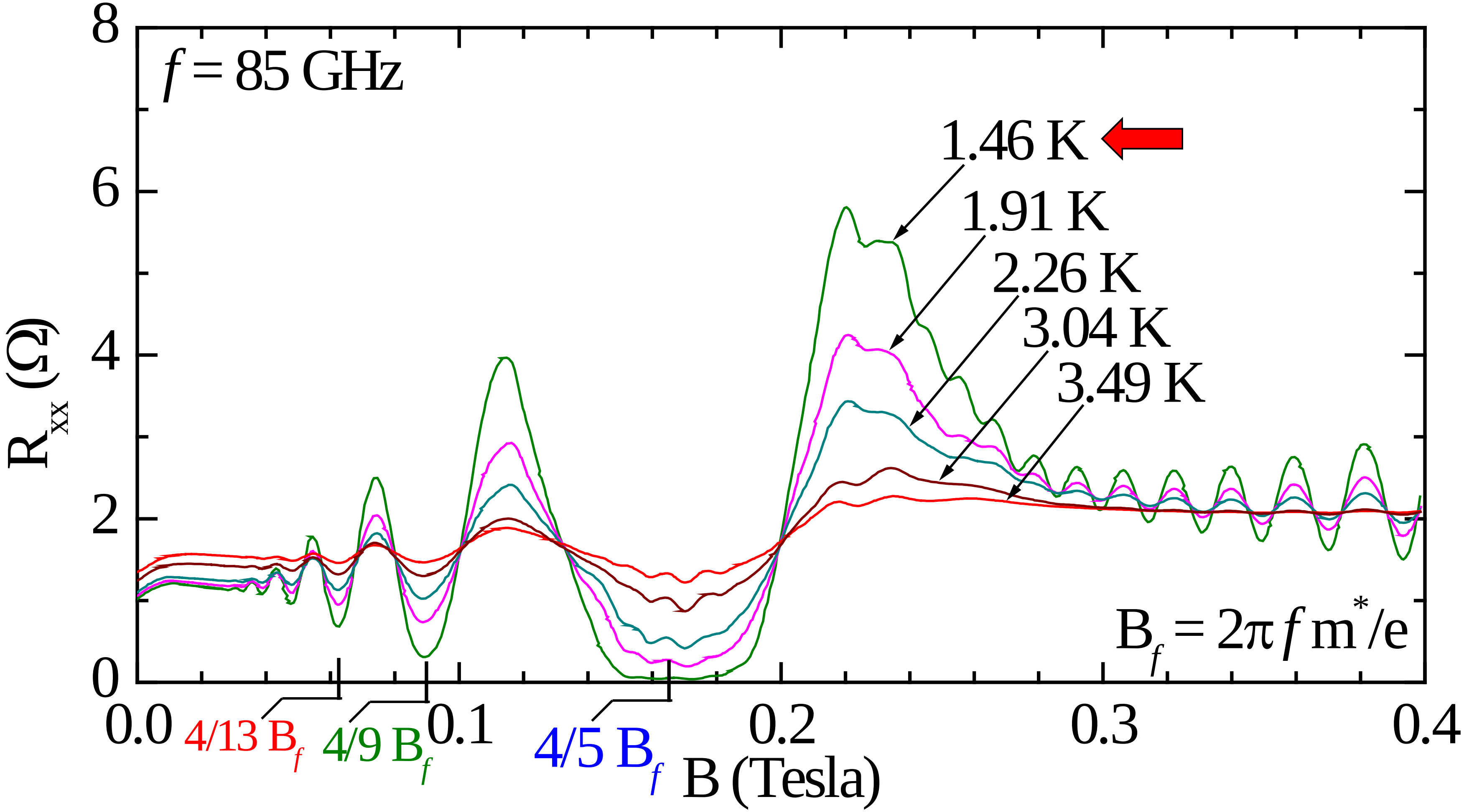
8
6
4
2
0
R_{xx} (Ω)
f = 85 GHz
3.04 K
3.49 K
$B_f = 2\pi f m^*/e$
0.0
0.1
0.2
0.3
0.4
4/13 B_f
4/9 B_f
4/5 B_f
B (Tesla)



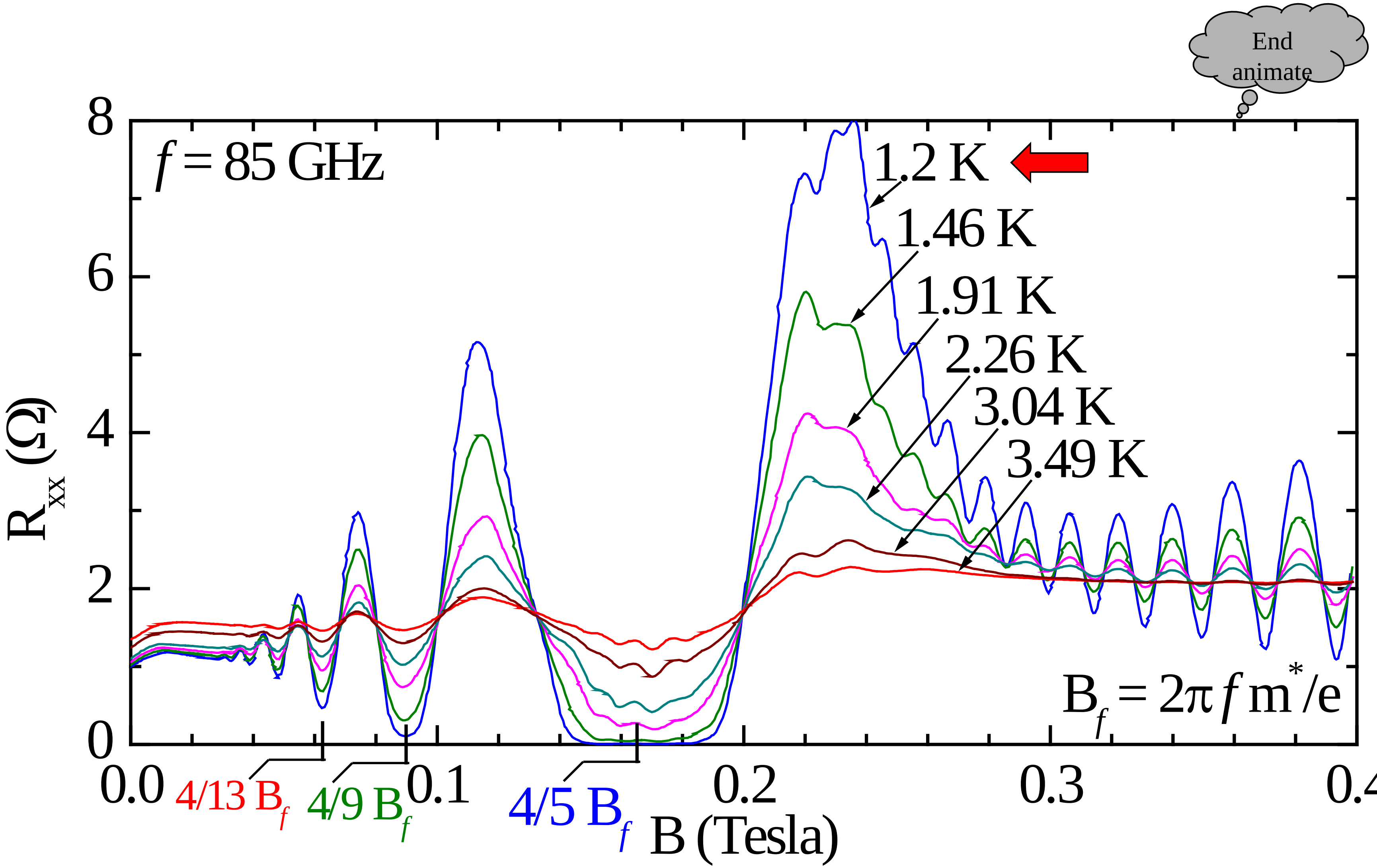
8
6
4
2
0
R_{xx} (Ω)
f = 85 GHz
2.26 K
3.04 K
3.49 K
$B_f = 2\pi f m^*/e$
0.0
0.1
0.2
0.3
0.4
4/13 B_f
4/9 B_f
4/5 B_f
B (Tesla)



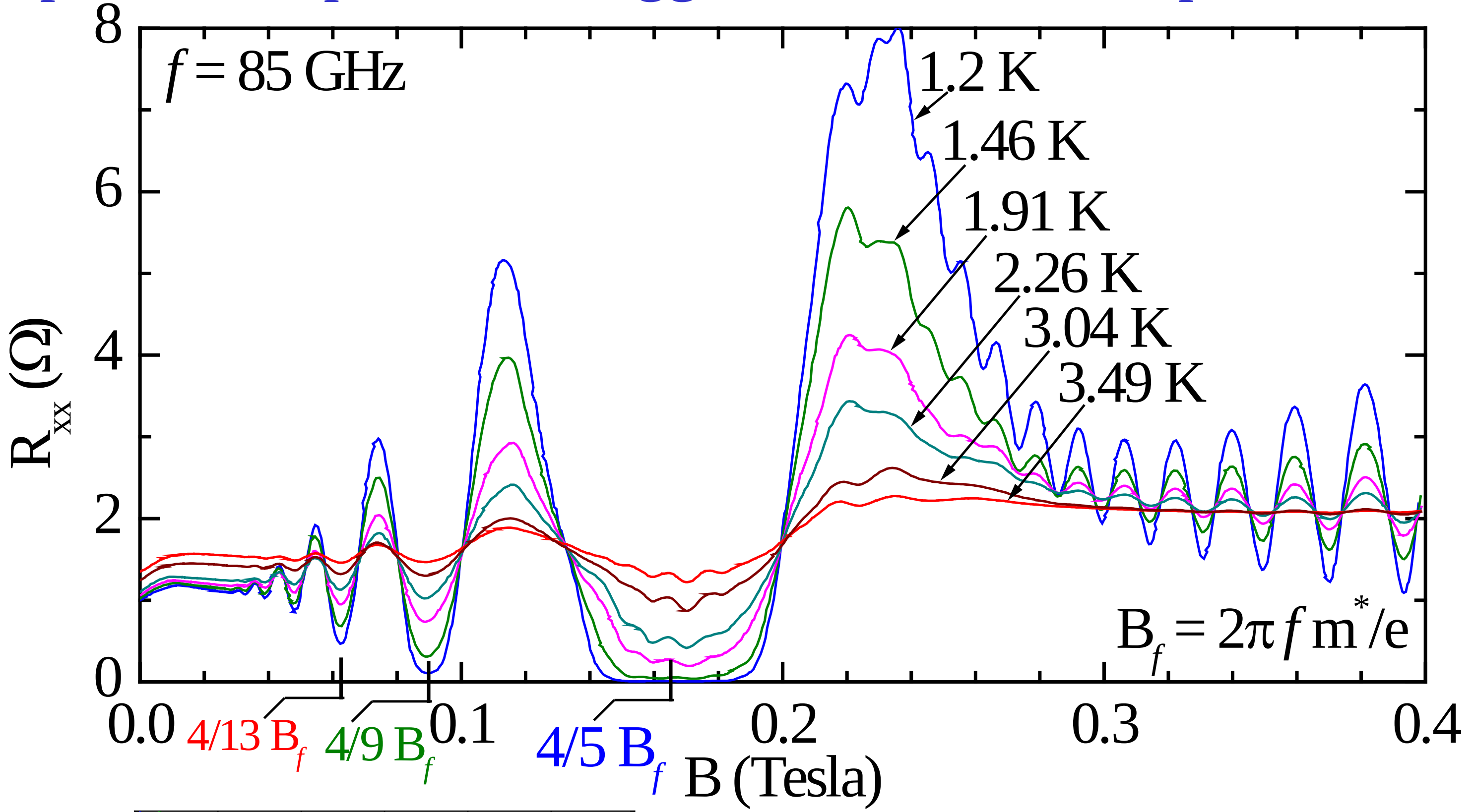
8
6
4
2
0
R_{xx} (Ω)
f = 85 GHz
1.91 K
2.26 K
3.04 K
3.49 K
$B_f = 2\pi f m^*/e$
0.0
0.1
0.2
0.3
0.4
4/13 B_f
4/9 B_f
4/5 B_f
B (Tesla)

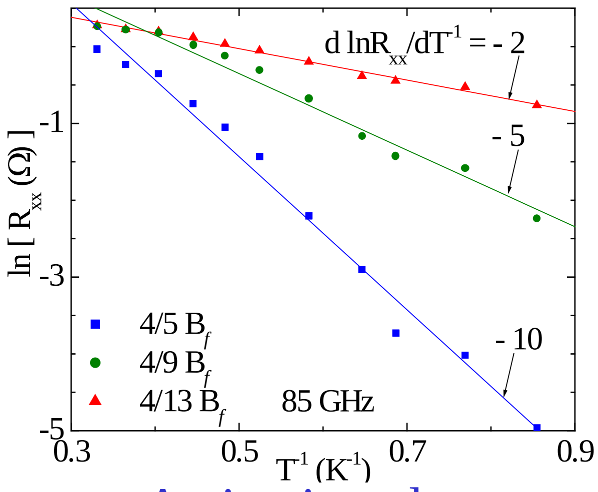


f = 85 GHz
1.46 K
1.91 K
2.26 K
3.04 K
3.49 K
B_f = 2π f m*/e
R_xx (Ω)
B (Tesla)
4/13 B_f
4/9 B_f
4/5 B_f
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4


End animate
f = 85 GHz
1.2 K
1.46 K
1.91 K
2.26 K
3.04 K
3.49 K
$B_f = 2\pi f m^*/e$
R_{xx} (Ω)
B (Tesla)
4/13 B_f
4/9 B_f
4/5 B_f

Temperature dependence suggests activated transport at the minima





Activation plot

Activated transport at resistance minima is reminiscent of QHE case

Mobility gap formation?

Outline

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- ZRS analogs in other 2D systems: e^- on liquid helium

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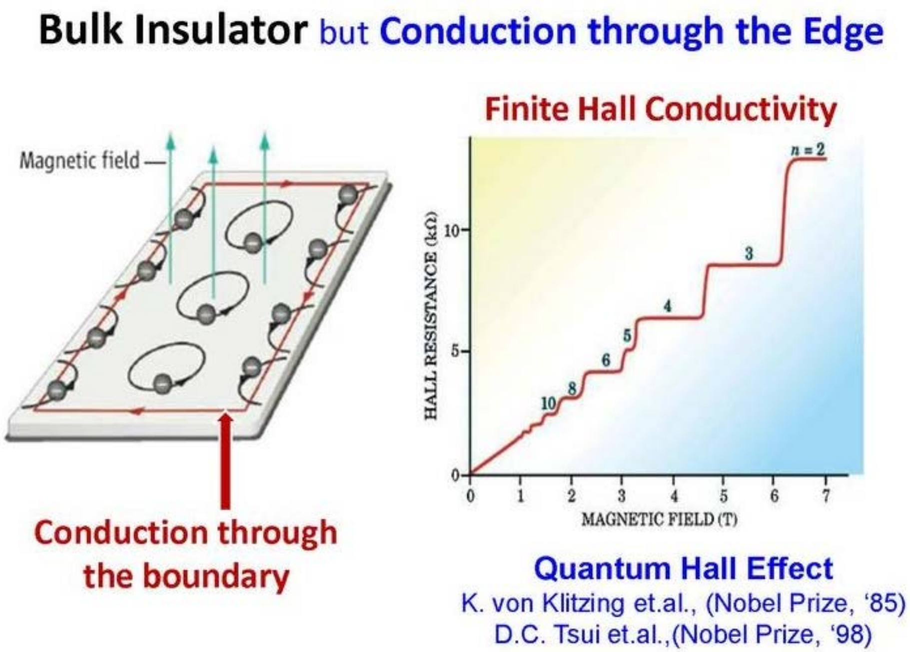
- Conclusion

Is it possible to bring together the radiation-induced zero-resistance states with the quantum Hall effect?

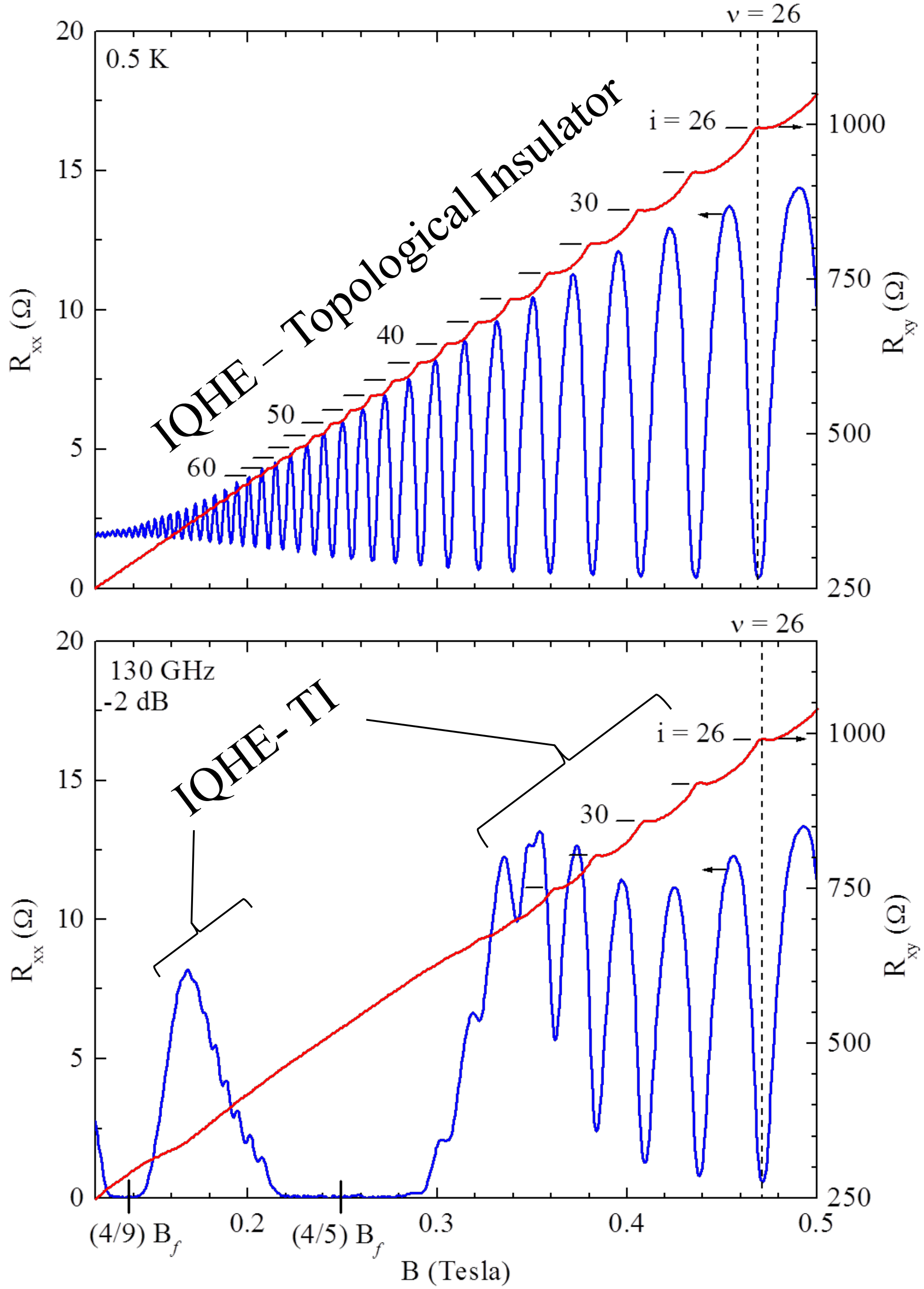


What will happen to the two effects when they meet?

How to bring the two-effects together?

- Increase the microwave frequency, shift radiation-induced magnetoresistance to higher magnetic fields dark

w/ microwaves

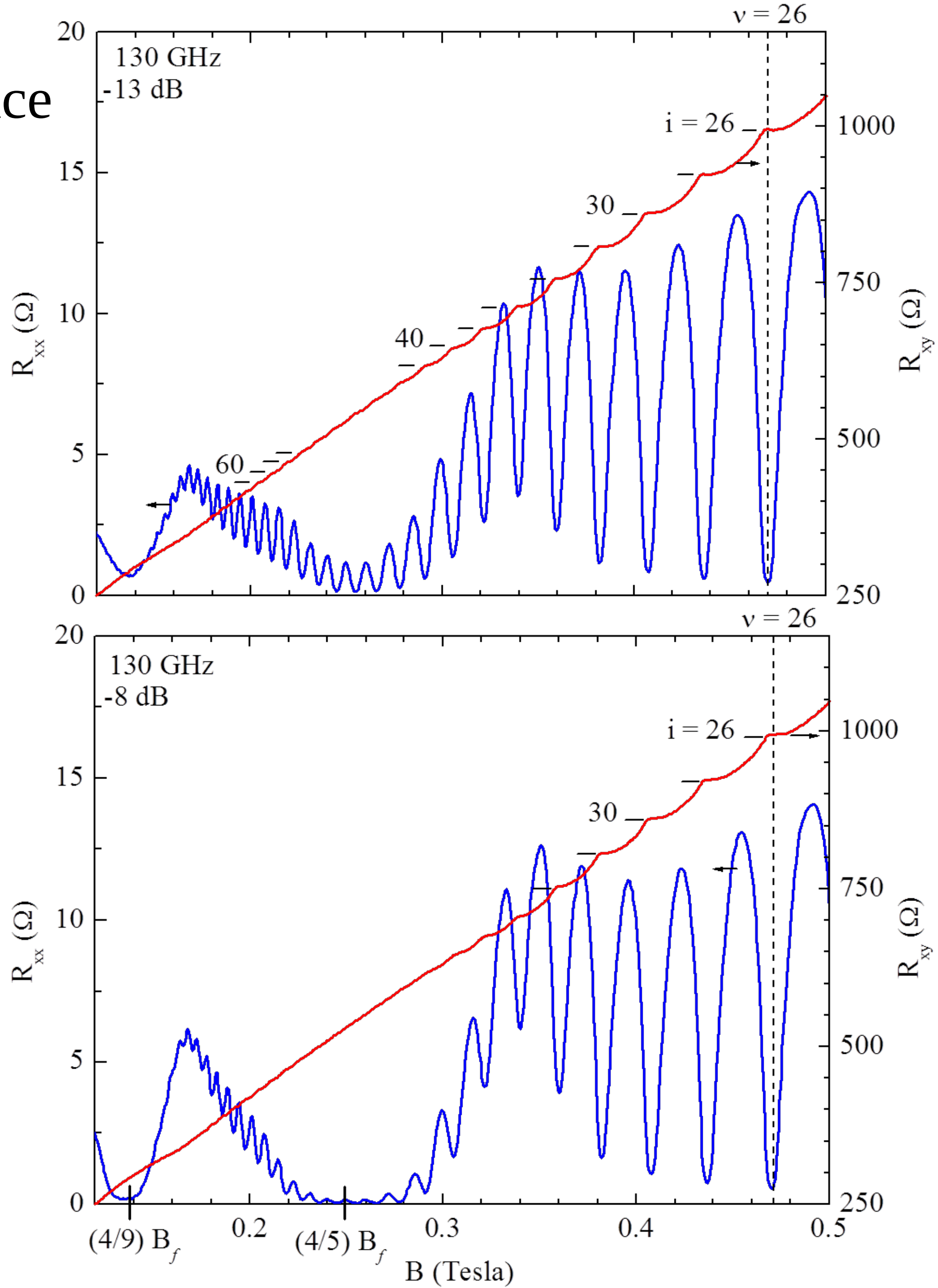


R. G. Mani et al., Phys. Rev. B 79 205320 (2009)

Power dependence

Less power

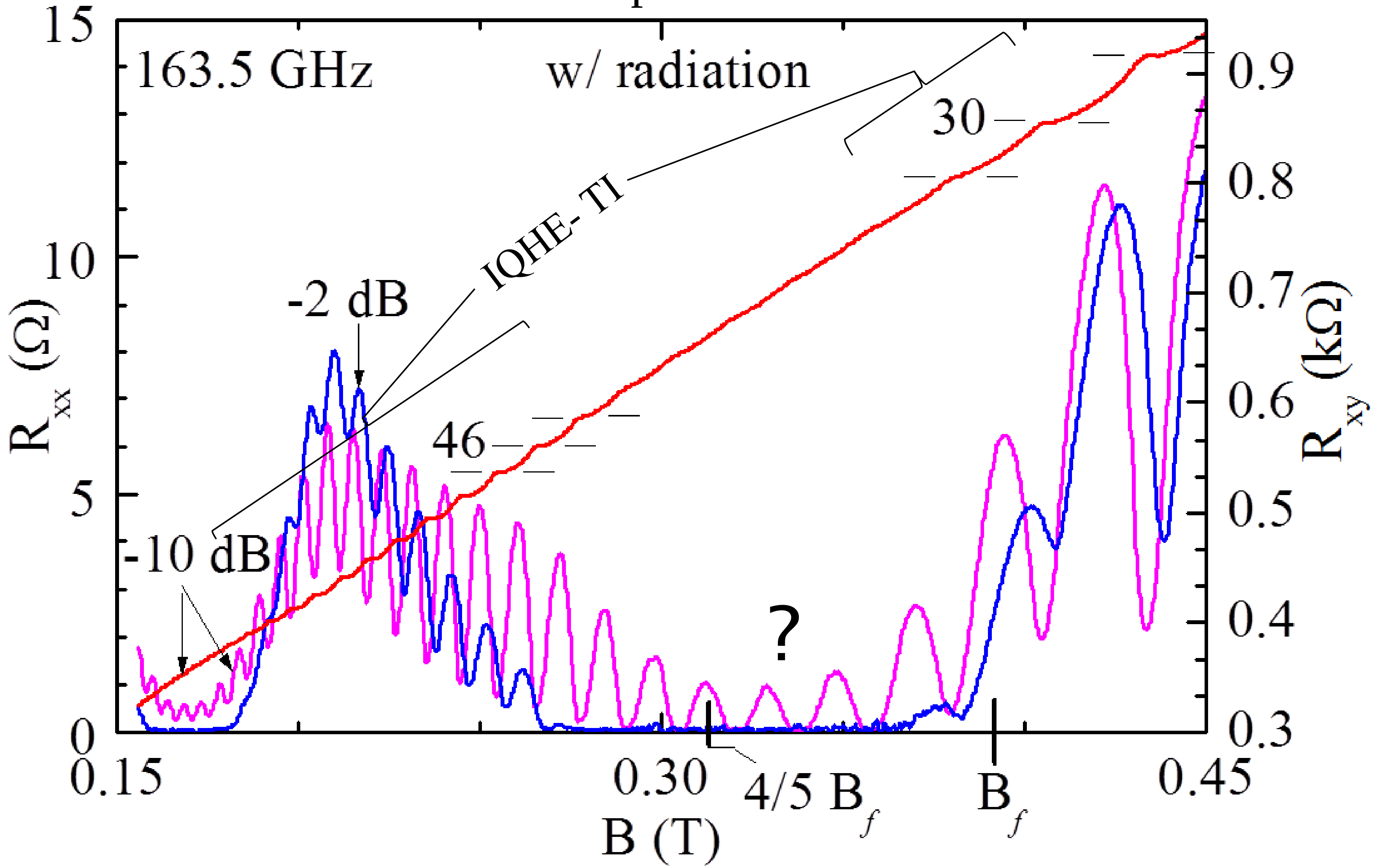
More power



R. G. Mani et al., Phys. Rev. B 79 205320 (2009)

Higher frequency, clear re-entrant IQHE under microwave excitation

Different power levels



Zero-resistance states overwhelm IQHE

R. G. Mani et al., Phys. Rev. B 79 205320 (2009)

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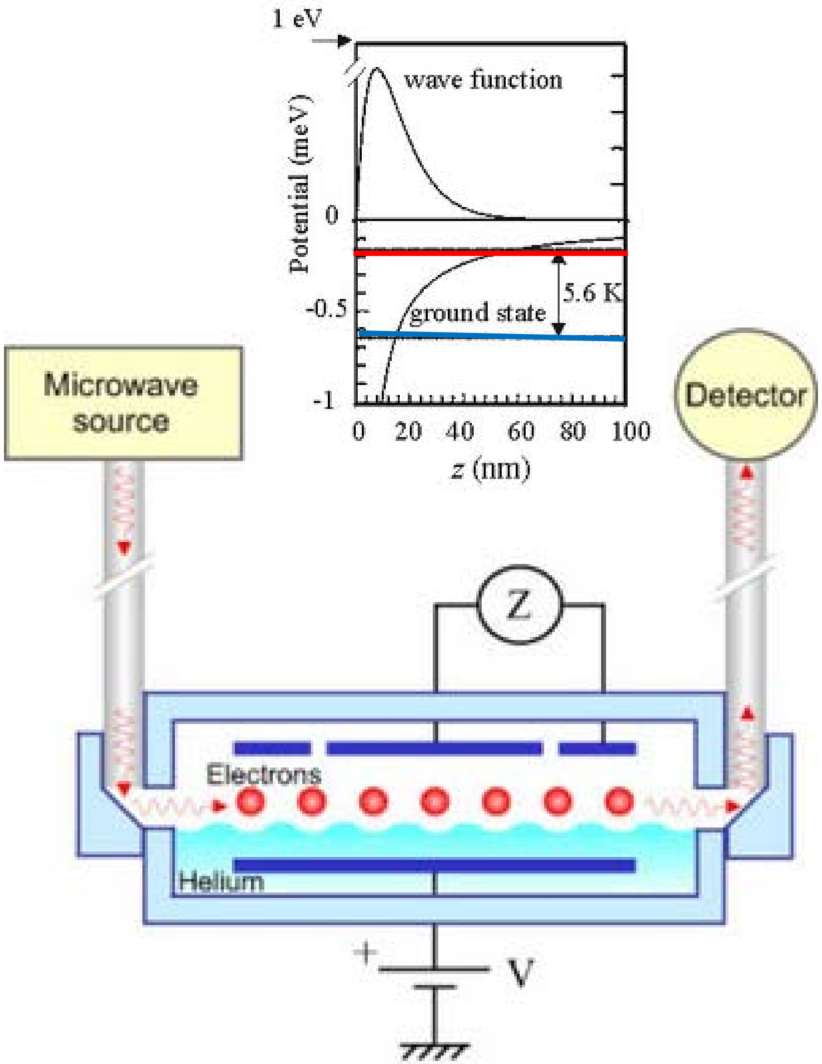
Is it possible to obtain zero-resistance states in other 2D electron systems:

- Requirement: clean, high mobility 2D electrons/holes
- Candidate:
  - → Electrons on liquid helium



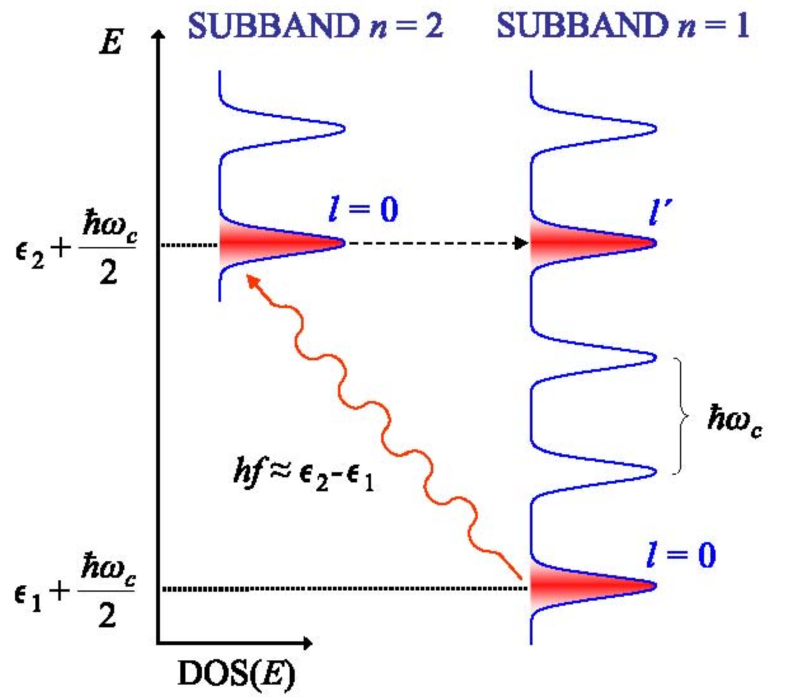


FIG. 1 (color online). Electron dynamics in perpendicular magnetic fields. Microwave photons of energy hf drive the transition $n = 1 \rightarrow 2$ (wavy arrow) without changing the quantum state l. Excited electrons can be scattered elastically (dashed arrow) and fill the state $l' > l$ of the first subband.

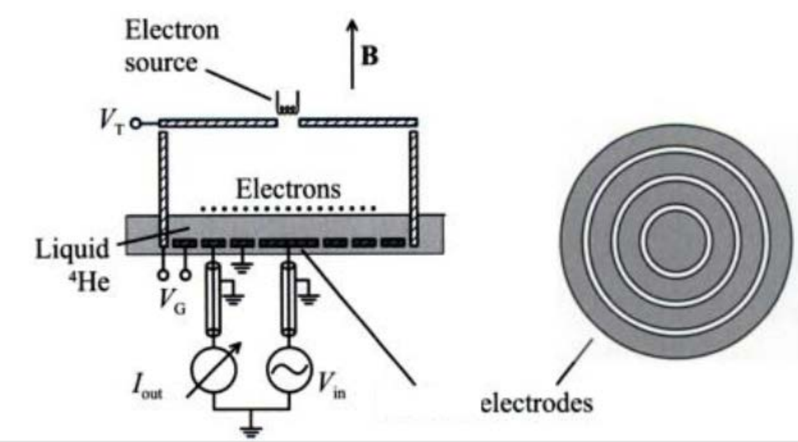
Novel Radiation-Induced Magnetoresistance Oscillations in a Nondegenerate Two-Dimensional Electron System on Liquid Helium

Denis Konstantinov* and Kimitoshi Kono

Low Temperature Physics Laboratory, RIKEN, Hirosawa 2-1, Wako 351-0198, Japan, USA

(Received 2 November 2009; published 31 December 2009)

We report the observation of novel magnetoresistance oscillations induced by the resonant intersubband absorption in nondegenerate 2D electrons bound to the surface of liquid ^{3}He. The oscillations are periodic in B^{-1} and originate from the scattering-mediated transitions of the excited electrons into the Landau levels of the first subband. The structure of the oscillations is affected by the collision broadening of the Landau levels and by many-electron effects.



AC capacitive method in Corbino geometry

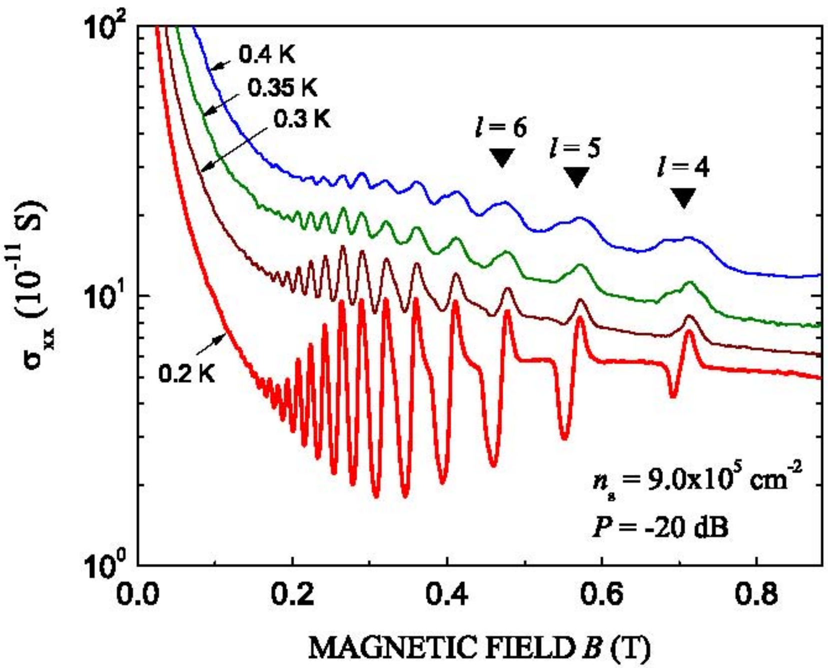


FIG. 2 (color online). Longitudinal conductivity σ_{xx} versus B for irradiated electrons with $n_s = 0.9 \times 10^6$ cm^{-2} at four different temperatures: $T = 0.4$ (blue line), 0.35 (green line), 0.3 (brown line), and 0.2 K (red line). Black triangles indicate the values of B where $hf = l\hbar\omega_c$, for $l = 4$, 5, and 6.

Photon-Induced Vanishing of Magnetoconductance in 2D Electrons on Liquid Helium

Denis Konstantinov* and Kimitoshi Kono

Low Temperature Physics Laboratory, RIKEN, Hirosawa 2-1, Wako 351-0198, Japan

(Received 17 May 2010; published 22 November 2010)

We report on a novel transport phenomenon realized by optical pumping in surface state electrons on helium subjected to perpendicular magnetic fields. The electron dynamics is governed by the photon-induced excitation and scattering-mediated transitions between electric subbands. In a range of magnetic fields, we observe vanishing longitudinal conductivity $\sigma_{xx} \to 0$. Our result suggests the existence of radiation-induced zero-resistance states in the nondegenerate 2D electron system.

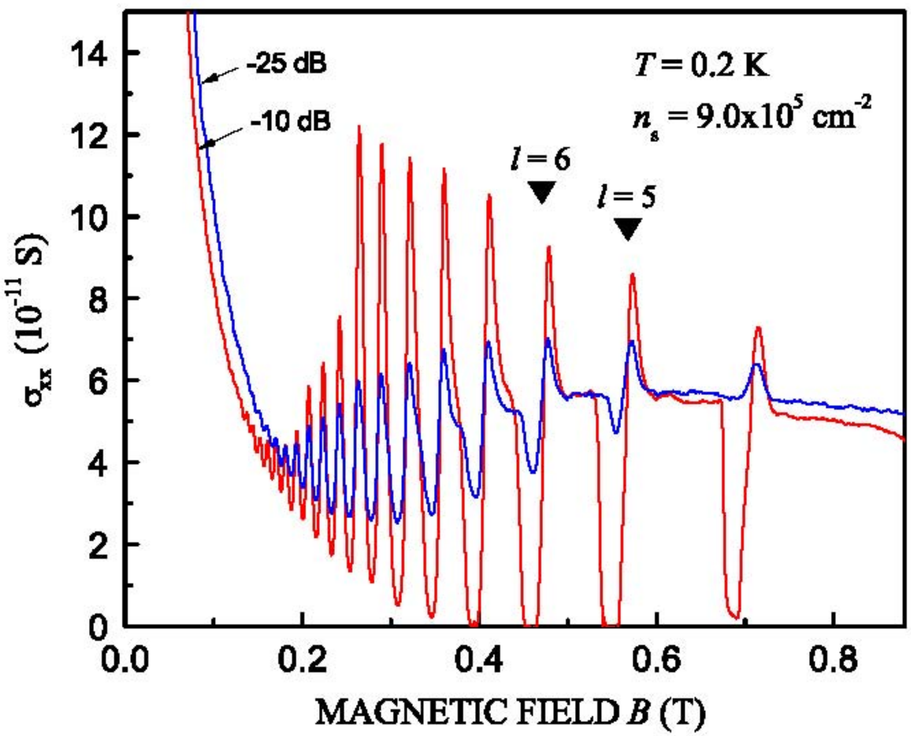


FIG. 3 (color online). σ_{xx} versus B for $n_s = 0.9 \times 10^6$ cm ^{2}, $T = 0.2$ K, and $P = -25$ (blue line) and -10 dB (red line).

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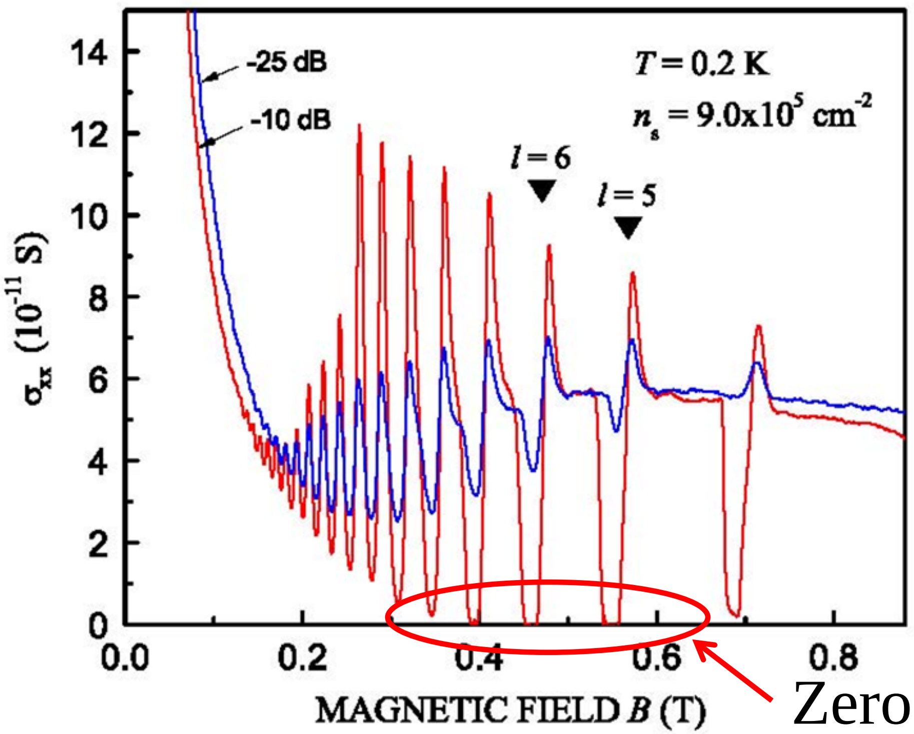

Zero-conductivity states

FIG. 3 (color online). σ_{xx} versus B for $n_s = 0.9 \times 10^6$ cm ^{2}, $T = 0.2$ K, and $P = -25$ (blue line) and -10 dB (red line).

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- **Review of theories**

- Conclusion

Some questions:

1) What is the mechanism that produces the radiation-induced magnetoresistance oscillations ?

2) How do zero-resistance states come about?

Theory: Radiation-induced magnetoresistance oscillations

Two contributions to the photoconductivity:

- $\sigma_{ph}^{(1)}$: influence of microwaves on impurity scattering : **Displacement Model**
  polarization dependent

Ryzhii, Durst et al., Lei and Liu, Shi and Xie,
Vavilov and Aleiner, Inarrea and Platero

- $\sigma_{ph}^{(2)}$: related to the change in the distribution function: **Inelastic Model**
  $\Rightarrow \propto \tau_{in}$, strongly T-dependent, independent of polarization

Dorozkin, Dmitriev et al.,

$$\sigma_{ph}^{(2)}/\sigma_{ph}^{(1)} \sim \tau_{in}/\tau_q >> 1 \text{ for relevant T}$$

$$\tau_{in}^{-1} \sim T^2/E_F \sim 10 \text{ mK}$$

Negative resistivity to zero-resistance:

Andreev et al.,
Auerbach et al.,
Finkler and Halperin

Others

Chepelianskii et al., Mikhailov

Radiation induced current through impurity scattering

A. C. Durst and Co.

VOLUME 91, NUMBER 8 PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2003

Radiation-Induced Magnetoresistance Oscillations in a 2D Electron Gas

Adam C. Durst, Subir Sachdev, N. Read, and S. M. Girvin

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(Received 30 January 2003; published 22 August 2003)

Recent measurements of a 2D electron gas subjected to microwave radiation reveal a magnetoresistance with an oscillatory dependence on the ratio of radiation frequency to cyclotron frequency. We perform a diagrammatic calculation and find radiation-induced resistivity oscillations with the correct period and phase. Results are explained via a simple picture of current induced by photoexcited disorder-scattered electrons. The oscillations increase with radiation intensity, easily exceeding the dark resistivity and resulting in negative-resistivity minima. At high intensity, we identify additional features, likely due to multiphoton processes, which have yet to be observed experimentally.

DOI: 10.1103/PhysRevLett.91.086803 PACS numbers: 73.40.–c, 73.43.–f, 78.67.–n

PACS numbers: 73.40.-c, 78.67.-n, 73.43.-f

The electrical transport properties of a 2D electron gas (2DEG) in a perpendicular magnetic field have been studied extensively over the past two decades in connection with the quantum Hall effects. However, recent experiments, in which such systems are subjected to electromagnetic radiation, reveal a surprising new phenomenon. The initial experiments of Zudov *et al.* [1], as well as more detailed subsequent studies conducted by Mani *et al.* [2] and Zudov *et al.* [3], show that a peculiar oscillation of the longitudinal resistance is induced by the presence of microwave radiation in systems at high filling factor. Unlike the familiar Shubnikov-de Haas oscillations which are controlled by the ratio of the chemical potential, μ, to the cyclotron frequency, ω_c, these radiation-induced oscillations are controlled by the ratio of the radiation frequency, ω, to the the cyclotron frequency. According to Ref. 2, the minimum resistance values are obtained near ω/ω_c = integer + 1/4. These results are surprising since naively one would only expect a peak at $\omega = \omega_c$ due to heating at the cyclotron resonance. Interest in this phenomenon was heightened when, using high mobility samples, both Mani *et al.* [2] and Zudov *et al.* [3] observed that as the radiation inten-

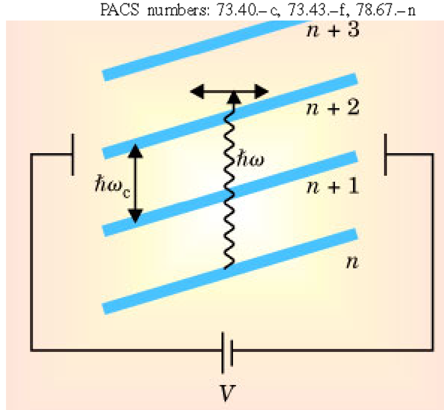

FIG. 1: Simple picture of radiation-induced disorder-assisted current. Landau levels are tilted by the applied dc bias. Electrons absorb photons and are excited by energy ω. Photo-excited electrons are scattered by disorder and kicked to the right or to the left by a distance $\pm d$. If the density of states to the left exceeds that to the right, current is enhanced. If vice versa, current is diminished.

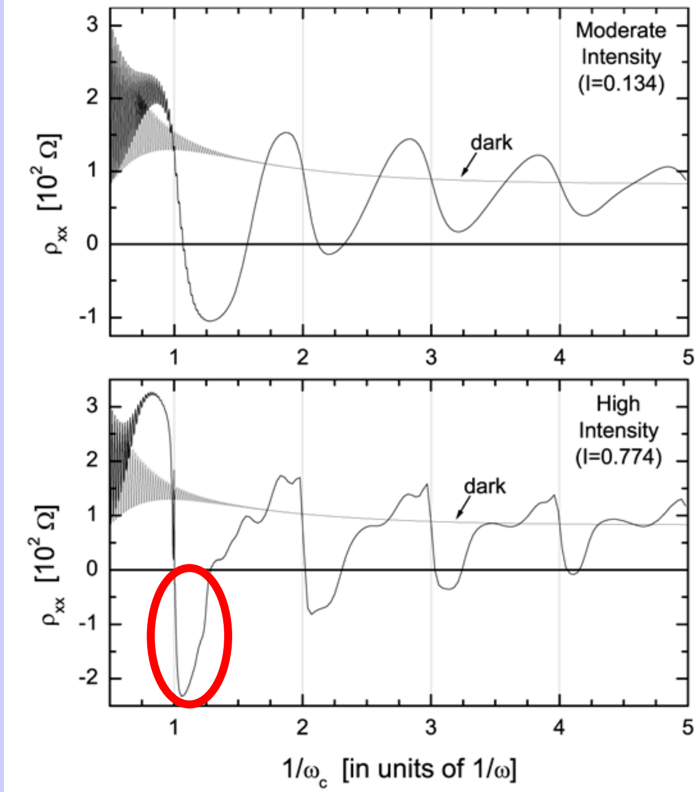

FIG. 3: Calculated longitudinal resistivity. We plot ρ_{xx} vs $1/\omega_c$ at fixed ω for $\mu = 50\omega$, $k_BT = \omega/4$, $= 0.08\omega$, and three values of radiation intensity (in units of $m^*\omega^3$): $I = 0$ (dark), $I = 0.134$, and $I = 0.774$ (see [10]). For computational purposes, the energy spectrum is cutoff at 20 Landau levels above and below the chemical potential. The high-frequency oscillations seen at small $1/\omega_c$ are the familiar Shubnikov-de Haas oscillations with period $1/\mu$. For moderate intensity (upper panel), the presence of radiation induces oscillations with period $1/\omega$ and minima near ω/ω_c = integer + 1/4. At higher intensity (lower panel), oscillation magnitude increases and additional features emerge which likely correspond to multiphoton effects.

- Current depends on difference between forward and reverse DOS (in x-direction)
- Theory suggests negative resistances

- Strong role for impurities in theory

Another mechanism for obtaining resistance oscillations with radiation

PHYSICAL REVIEW B **71**, 115316 (2005)

Theory of microwave-induced oscillations in the magnetoconductivity of a two-dimensional electron gas

I. A. Dmitriev,[1,*] M. G. Vavilov,[2] I. L. Aleiner,[3] A. D. Mirlin,[1,4,†] and D. G. Polyakov[1,*]
[1]*Institut für Nanotechnologie, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany*
[2]*Center for Materials Sciences and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Physics Department, Columbia University, New York, New York 10027, USA*
[4]*Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, 76128 Karlsruhe, Germany*
(Received 10 February 2004; revised manuscript received 22 September 2004; published 21 March 2005)

We develop a theory of magneto-oscillations in the photoconductivity of a two-dimensional electron gas observed in recent experiments. The effect is governed by a change of the electron distribution function induced by the microwave radiation. We analyze a nonlinearity with respect to both the dc field and the microwave power, as well as the temperature dependence determined by the inelastic relaxation rate.

DOI: 10.1103/PhysRevB.71.115316 PACS number(s): 73.40.−c, 73.43.−f, 76.40.+b, 78.67.−n

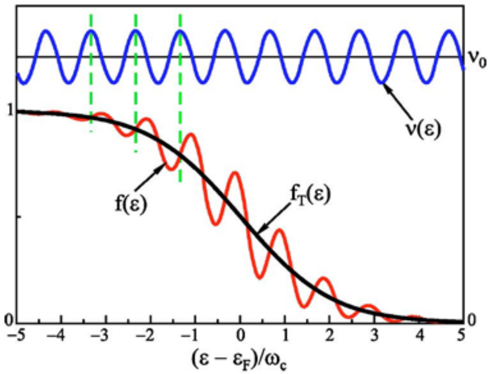

FIG. 1. (Color online) Schematic behavior of the oscillatory density of states $\nu(\varepsilon)$ and radiation induced oscillations in the distribution function $f(\varepsilon)$ for $\sin(2\pi\omega/\omega_c)>0$.

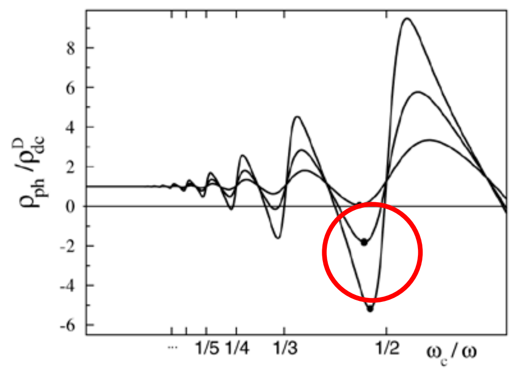

FIG. 1. Photoresistivity (normalized to the dark Drude value) for overlapping Landau levels vs ω_c/ω at fixed $\omega\tau_q = 2\pi$. The curves correspond to different levels of microwave power $\mathcal{P}_\omega^{(0)} = \{0.24, 0.8, 2.4\}$. Nonlinear $I-V$ characteristics at the marked minima are shown in Fig. 2.

How to go from negative resistivity to zero-resistance?

VOLUME 91, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2003

Dynamical Symmetry Breaking as the Origin of the Zero-dc-Resistance State in an ac-Driven System

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[1]*Physics Department, University of Colorado, Boulder, Colorado 80309, USA*
[2]*Bell Labs, Lucent Technologies, Room 1D-267, Murray Hill, New Jersey 07974, USA*
[3]*Physics Department, Columbia University, New York, New York 10027, USA*

(Received 3 February 2003; published 1 August 2003)

Under a strong ac drive the zero-frequency linear response dissipative resistivity $\rho_d(j = 0)$ of a homogeneous state is allowed to become negative. We show that such a state is absolutely unstable. The only time-independent state of a system with a $\rho_d(j = 0) < 0$ is characterized by a current which almost everywhere has a magnitude j_0 fixed by the condition that the nonlinear dissipative resistivity $\rho_d(j_0^2) = 0$. As a result, the dissipative component of the dc-electric field vanishes. The total current may be varied by rearranging the current pattern appropriately with the dissipative component of the dc-electric field remaining zero. This result, together with the calculation of Durst *et al.*, indicating the existence of regimes of applied ac microwave field and dc magnetic field where $\rho_d(j = 0) < 0$, explains the zero-resistance state observed by Mani *et al.* and Zudov *et al.*

DOI: 10.1103/PhysRevLett.91.056803 PACS numbers: 73.40.–c, 05.65.+b, 73.43.–f, 78.67.–n

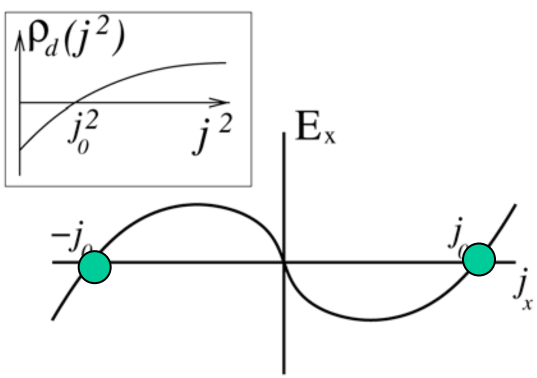

FIG. 1: Conjectured dependence of the dissipative component of the local electric field E_x on the current density j_x. The inset shows the current dependence of the dissipative resistivity.

- Negative resistivity is unstable!
- Assume: the resistivity is a function of current
- Currents are setup such that the resistance vanishes

Other approaches:

PHYSICAL REVIEW B **80**, 241308(R) (2009)

Microwave stabilization of edge transport and zero-resistance states

A. D. Chepelianskii[1] and D. L. Shepelyansky[2,3]
[1]*LPS, Université Paris-Sud, CNRS, UMR 8502, F-91405 Orsay, France*
[2]*Université de Toulouse, UPS, Laboratoire de Physique Théorique (IRSAMC), F-31062 Toulouse, France*
[3]*CNRS, LPT (IRSAMC), F-31062 Toulouse, France*

(Received 5 May 2009; revised manuscript received 24 November 2009; published 16 December 2009)

Edge channels play a crucial role for electron transport in two-dimensional electron gas under magnetic field. It is usually thought that ballistic transport along edges occurs only in the quantum regime with low filling factors. We show that a microwave field can stabilize edge trajectories even in the semiclassical regime leading to a vanishing longitudinal resistance. This mechanism gives a clear physical interpretation for observed zero-resistance states.

PHYSICAL REVIEW B **80**, 241308(R) (2009)

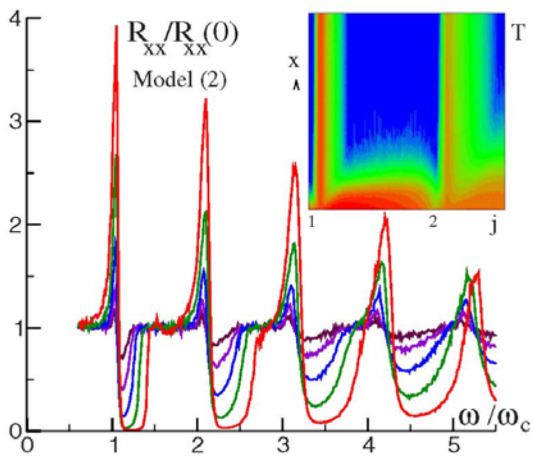

FIG. 3. (Color online) Dependence of rescaled R_{xx} in model (2) on ω/ω_c for microwave fields ϵ=0.00375, 0.0075, 0.015, 0.03, and 0.06 (curves from top to bottom at $j=\omega/\omega_c=4.5$); $\gamma_c=0.01$, $\alpha=0.03$. Average is done over 10^4 particles and 5000 map iterations. The inset shows transmission probability T at distance x along the edge for $\epsilon=0.02$ (red/gray is for maximum and blue/black for zero, $0<x<10^3 v_F/\omega$).

Insulating bulk,
Conducting edges

PHYSICAL REVIEW B **83**, 155303 (2011)

Theory of microwave-induced zero-resistance states in two-dimensional electron systems

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(Received 25 November 2010; revised manuscript received 19 January 2011; published 6 April 2011)

The phenomena of microwave-induced zero-resistance states (MIZRS) and microwave-induced resistance oscillations (MIRO) were discovered in ultraclean two-dimensional electron systems in 2001–2003 and have attracted great interest from researchers. In spite of numerous theoretical efforts, the true origin of these effects remains unknown so far. We show that the MIRO-ZRS phenomena are naturally explained by the influence of the ponderomotive forces which arise in the near-contact regions of two-dimensional electron gas under the action of microwaves. The proposed analytical theory is in agreement with all experimental facts accumulated so far and provides a simple and self-evident explanation of the microwave frequency, polarization, magnetic field, mobility, power, and temperature dependencies of the observed effects.

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Theory of microwave-induced zero-resistance states in two-dimensional electron systems

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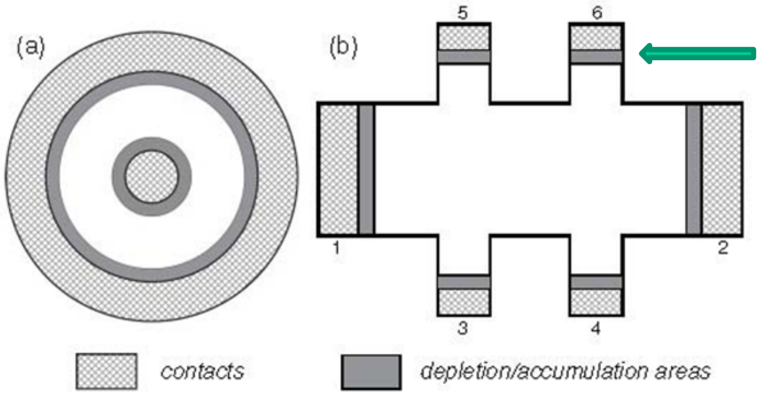


FIG. 4. The geometry of (a) the Corbino disk and (b) the Hall-bar sample under intense microwave irradiation. The gray areas near the contacts show the microwave-induced depletion/accumulation regions.

Depletion/accumulation near contacts due to pondermotive forces

Pondermotive force: a charged particle in an inhomogeneous oscillating field not only oscillates at the frequency of ω but also drifts toward the weak field area

S. A. Mikhailov, PRB 83, 153303, 2011

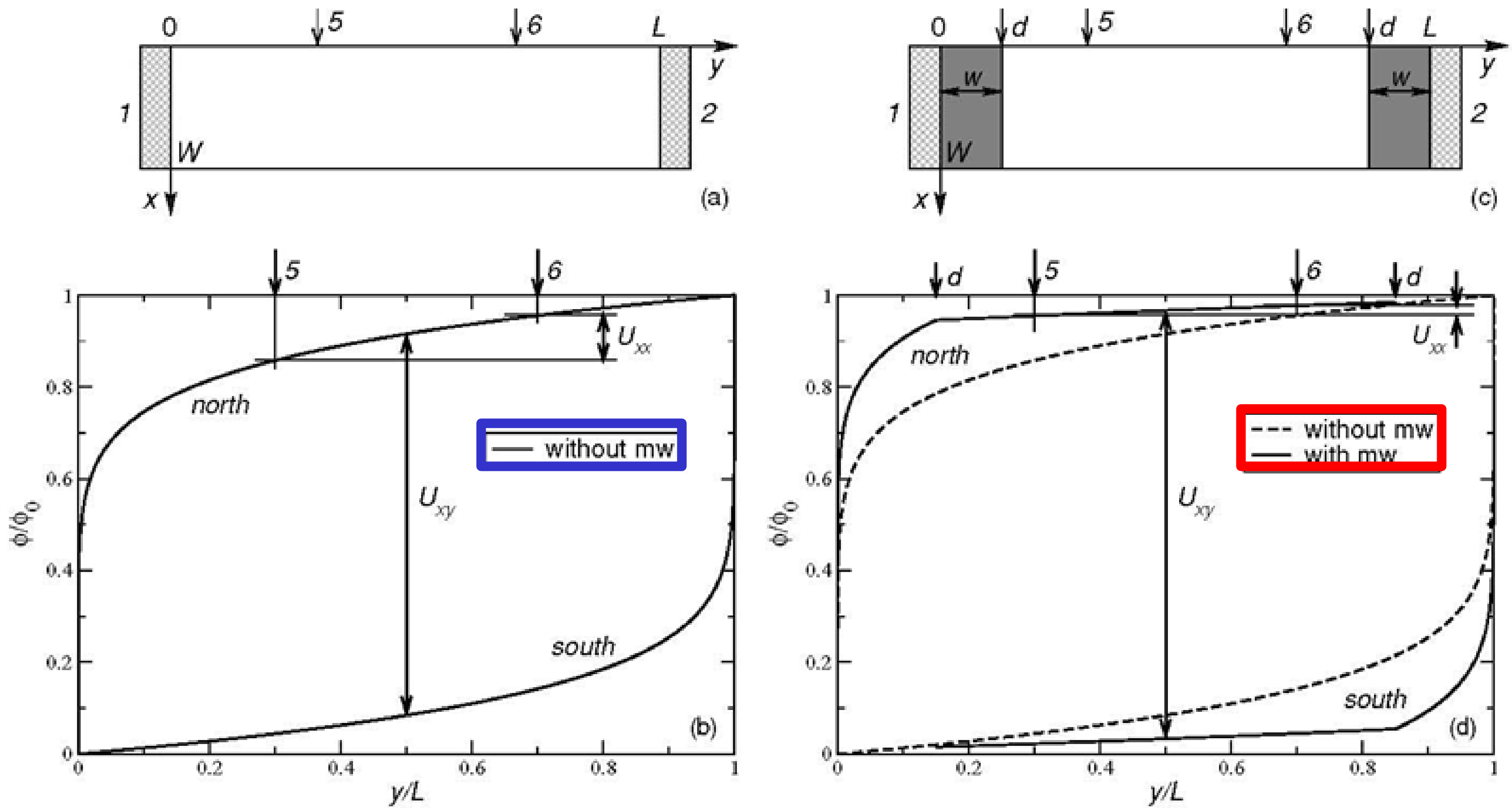


FIG. 5. (a),(c) A rectangular sample with $\phi(x,0) = 0$ ("west" contact) and $\phi(x,L) = \phi_0$ ("east" contact) (a) in the absence of microwaves and (c) irradiated by microwaves. The boundary conditions at the "north" and "south" sides of the rectangle are $j_x(0,y) = j_x(W,y) = 0$. W is the sample width in the x direction and L is the sample length in the y direction; the arrows 5 and 6 show the position of the contacts; the arrows d show the boundaries of the depletion layers. (b),(d) The distribution of the dc electric potential on the "north" and "south" sides of the rectangle (b) in the absence of microwaves and (d) under the microwave irradiation. U_{xy} and U_{xx} schematically show the measured values of the Hall and diagonal voltages.

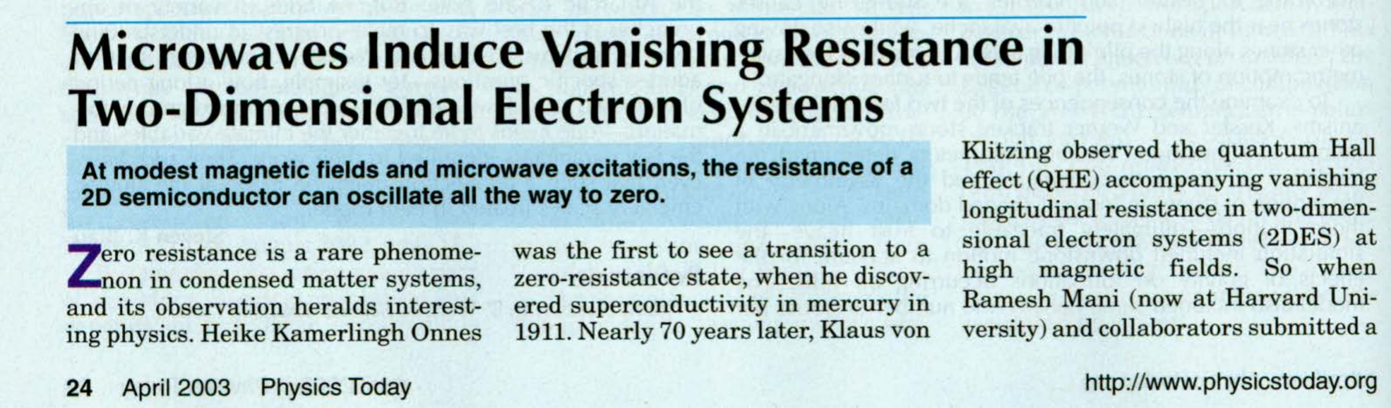
Outline

- Experimental details

- The basic zero-resistance effect
- Tilt field experiment: 2D orbital effect
- Temperature dependence: Activated transport
- Examine overlap of zero-resistance states and quantum Hall effect
- ZRS analogs in other 2D systems: e^- on liquid helium

- Review of theories

- **Summary**



Microwaves Induce Vanishing Resistance in Two-Dimensional Electron Systems

At modest magnetic fields and microwave excitations, the resistance of a 2D semiconductor can oscillate all the way to zero.

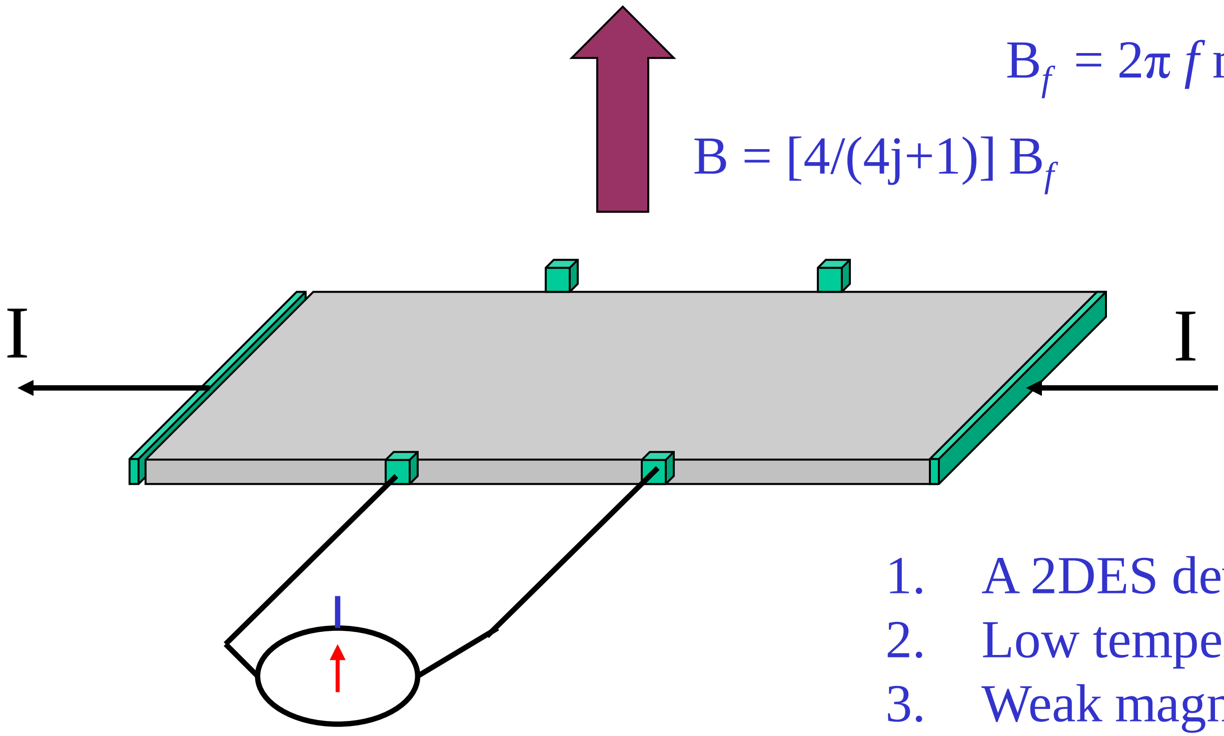
Zero resistance is a rare phenomenon in condensed matter systems, and its observation heralds interesting physics. Heike Kamerlingh Onnes was the first to see a transition to a zero-resistance state, when he discovered superconductivity in mercury in 1911. Nearly 70 years later, Klaus von Klitzing observed the quantum Hall effect (QHE) accompanying vanishing longitudinal resistance in two-dimensional electron systems (2DES) at high magnetic fields. So when Ramesh Mani (now at Harvard University) and collaborators submitted a

f

Summary:

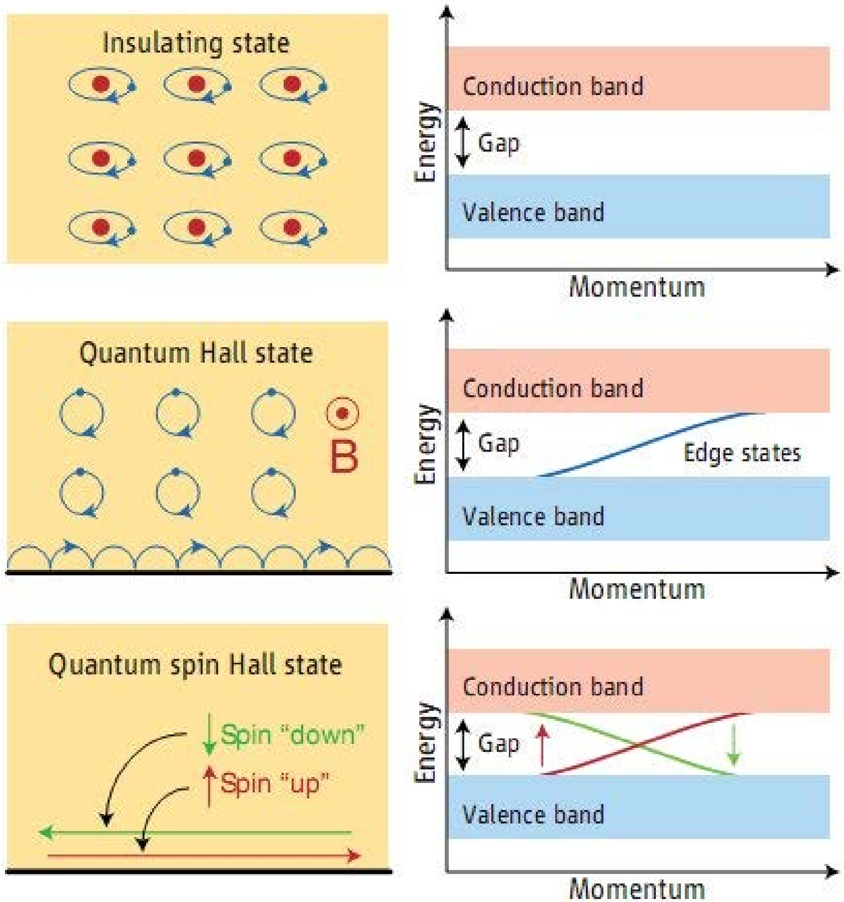
$B_f = 2\pi f m^*/e$

$B = [4/(4j+1)] B_f$ $j = 1, 2, 3\ldots$



1. A 2DES device
2. Low temperature, ~ 1.5 K
3. Weak magnetic field
4. Low energy photons, f

Some examples of insulators

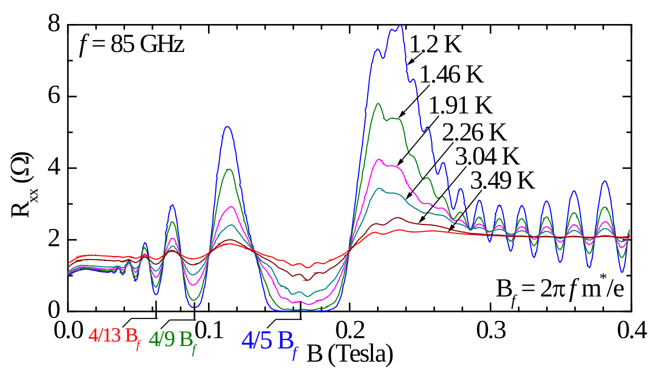


Band insulator

Quantum Hall effect:
Topological insulator

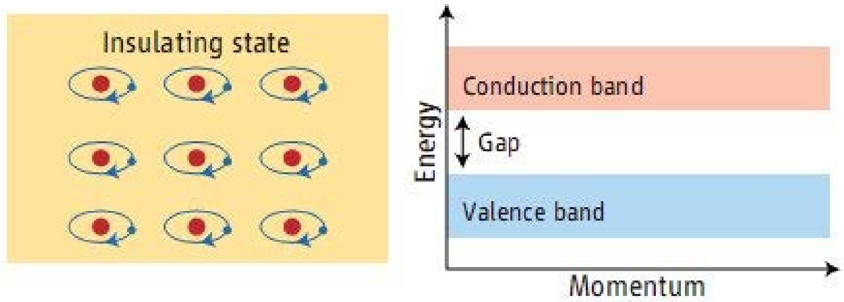
QSHE:
Topological insulator
(strong spin-orbit interaction)

- Kane & Mele

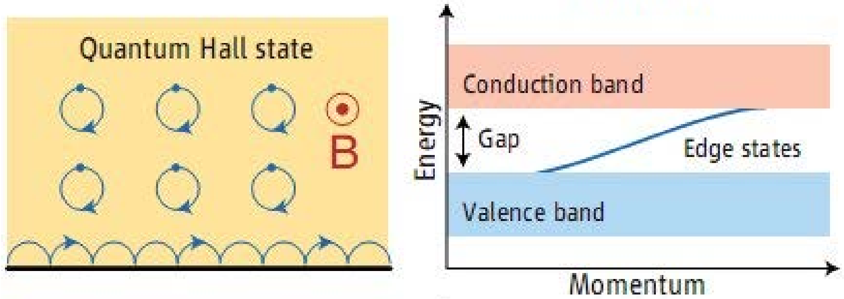


ZRS: conducting insulator
Is it a topologically insulating phase or broken symmetry phase?

Some examples of insulators



Band insulator



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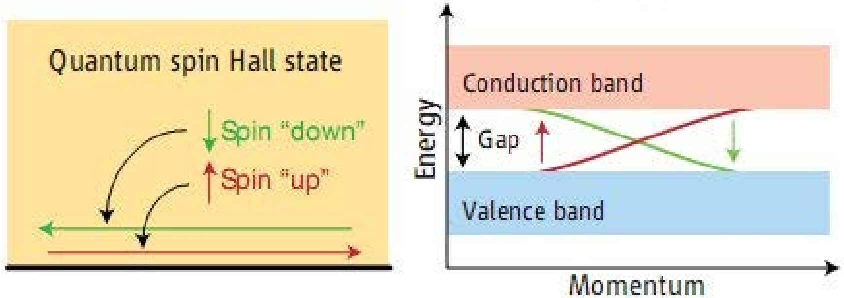

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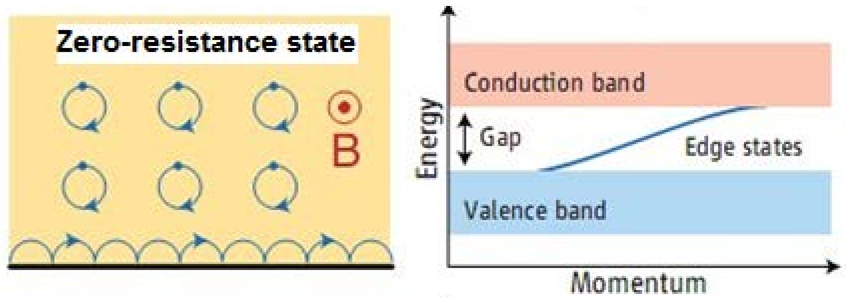

Topologically insulating phase or broken symmetry phase?

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Other approaches to zero-resistance

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THE EUROPEAN PHYSICAL JOURNAL B

Synchronization, zero-resistance states and rotating Wigner crystal

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Abstract. We show, in a framework of a classical nonequilibrium model, that rotational angles of electrons moving in two dimensions (2D) in a perpendicular magnetic field can be synchronized by an external microwave field whose frequency is close to the Larmor frequency. The synchronization eliminates collisions between electrons and thus creates a regime with zero diffusion corresponding to the zero-resistance states observed in experiments with high mobility 2D electron gas (2DEG). For long range Coulomb interactions electrons form a rotating hexagonal Wigner crystal. Possible relevance of this effect of synchronization-induced self-assembly for planetary rings is discussed.

PACS. 73.40.-c Electronic transport in interface structures – 05.45.Xt Synchronization; coupled oscillators – 05.20.-y Classical statistical mechanics

The discovery of microwave-induced resistance oscillations (MIRO) [1] and of striking zero-resistance states (ZRS) of a 2DEG in a magnetic field [2,3] attracted a great interest of the community. A variety of theoretical explanations has been pushed forward to explain the appearance of ZRS (see Refs. in [4]). Many of these approaches provide certain MIRO which at large microwave power even produce a current inversion. Although there are arguments in the literature that ZRS are created as a result of some additional instabilities which may compensate currents to zero, the understanding of underlying mechanisms is missing. Hence, a physical origin of ZRS still remains a puzzling, challenging problem.

coherent dynamics is typical for synchronization in ensembles of nonequilibrium oscillators; quite understood physical examples are laser arrays and networks of Josephson junctions, but one observes such a synchronization also in non-physical systems like populations of blinking fireflies [5,6], pedestrians on a bridge [7], and applauding audience [8]. But compared to other oscillators, the synchronization of moving electrons brings a new element not presented in the common synchronization studies: due to synchrony the collisions between electrons disappear. This leads to a drastic drop of the collision-induced diffusion constant D and to creation of ZRS. We note that the diffusion D is proportional to experimentally mea-

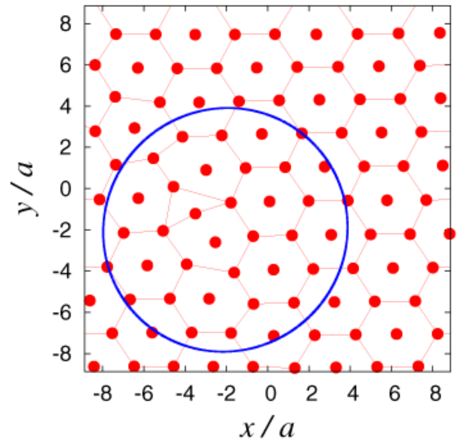

FIG. 4: (color online) Instant image of the rotating Wigner crystal formed by $N = 100$ electrons (points) in a periodic cell with $L = \sqrt{N/\rho} \approx 17.72a$, $\omega t = 480$, $\omega_B = \omega$, $fa/E_F = 0.02$ and $N_B = 34.7$ (as in Fig. 2, bottom curve); the circle shows an orbit of one electron for $240 \leq \omega t \leq 480$; lines are drawn to adapt an eye showing a hexagonal crystal with a defect.

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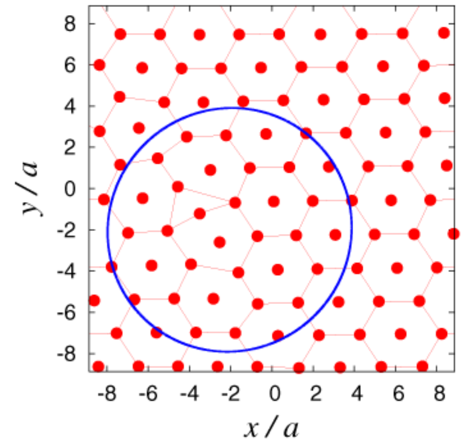

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