QT2DS-Luchon – 5/28/2015

Microwave-induced transport
Transport characteristics of the microwave driven 2D negative magneto-conductivity state

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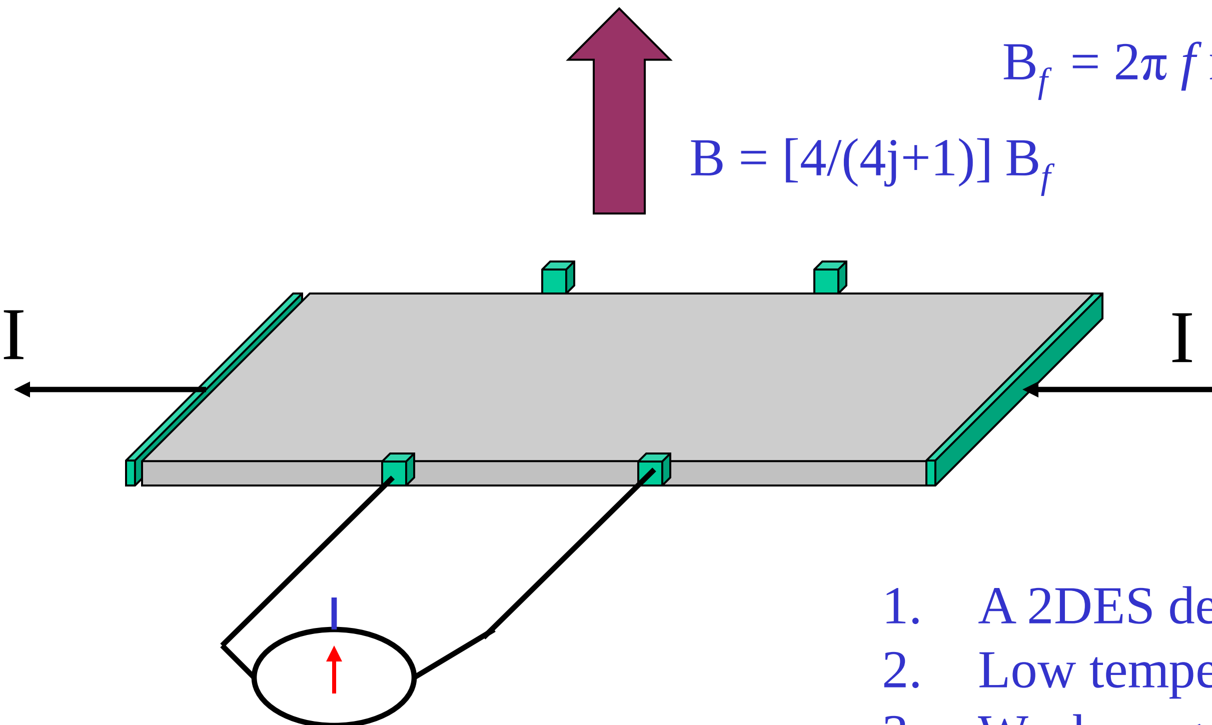
Radiation-induced zero-resistance-states in the 2DES

f

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

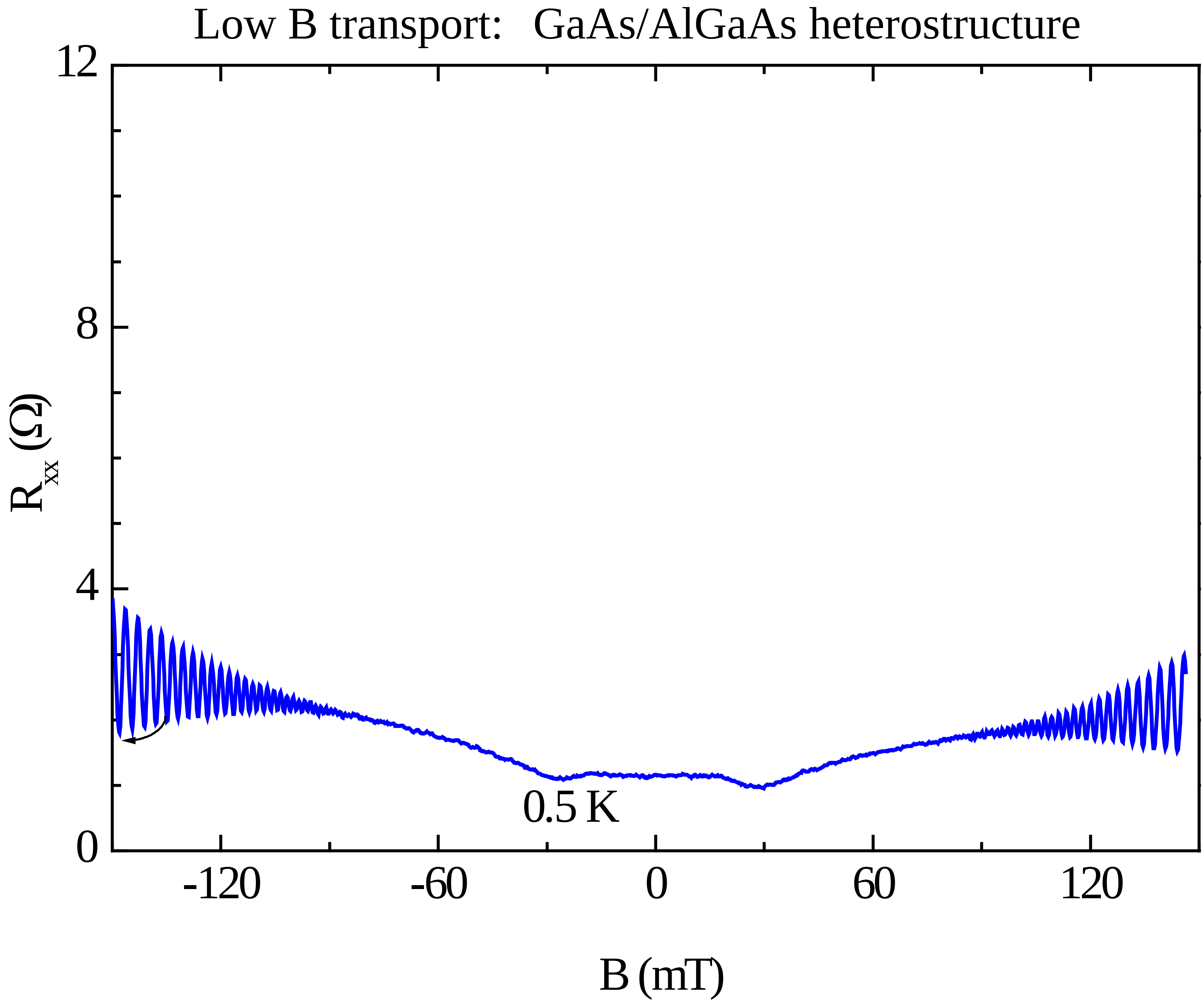
$B = [4/(4j+1)] B_f$ $\quad j = 1, 2, 3\ldots$



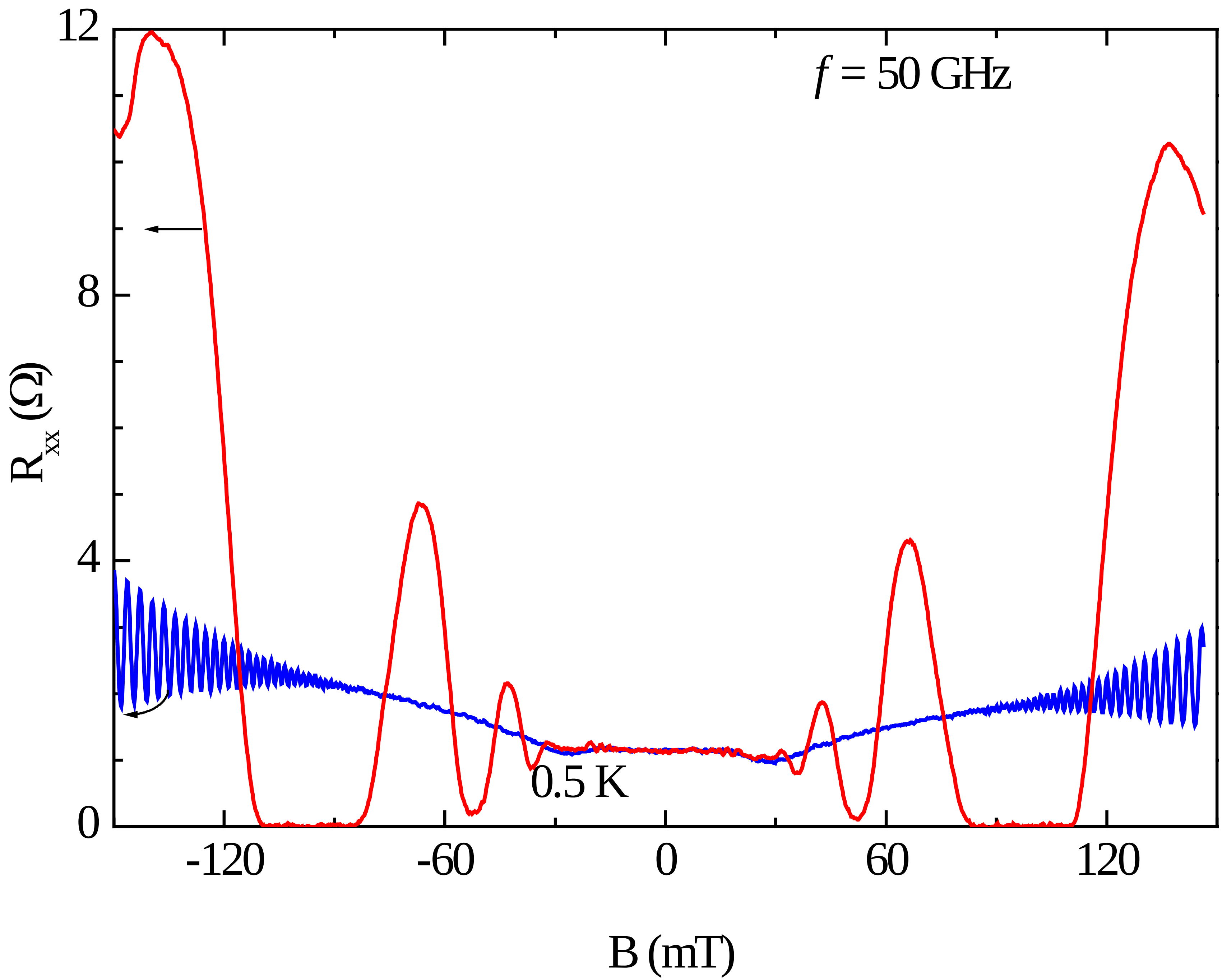
1. A 2DES device
2. Low temperature, ~ 1.5 K
3. Weak magnetic field
4. Low energy photons, f

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

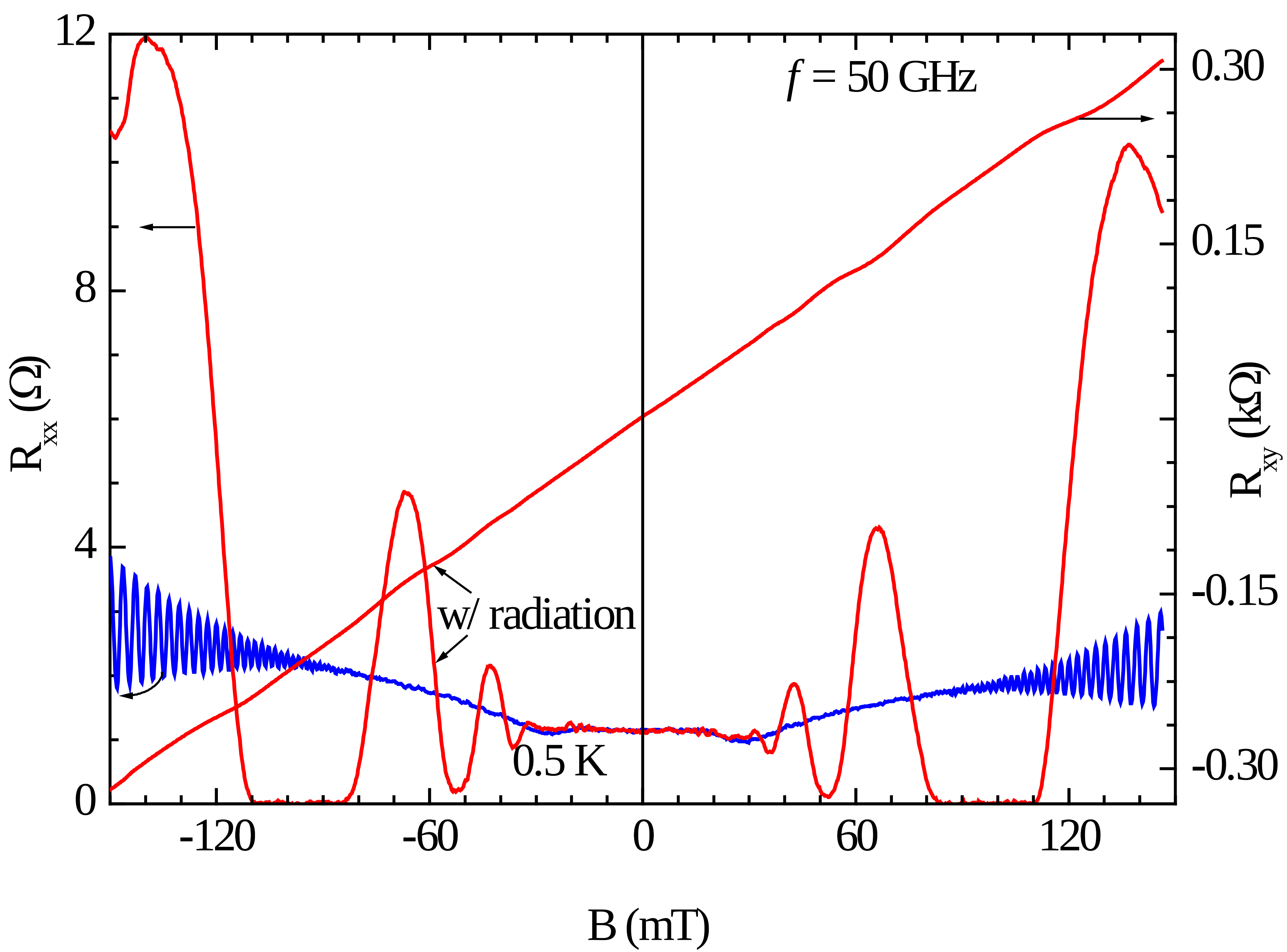
M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. West, Phys. Rev. Lett. 90, 046807 (2003).



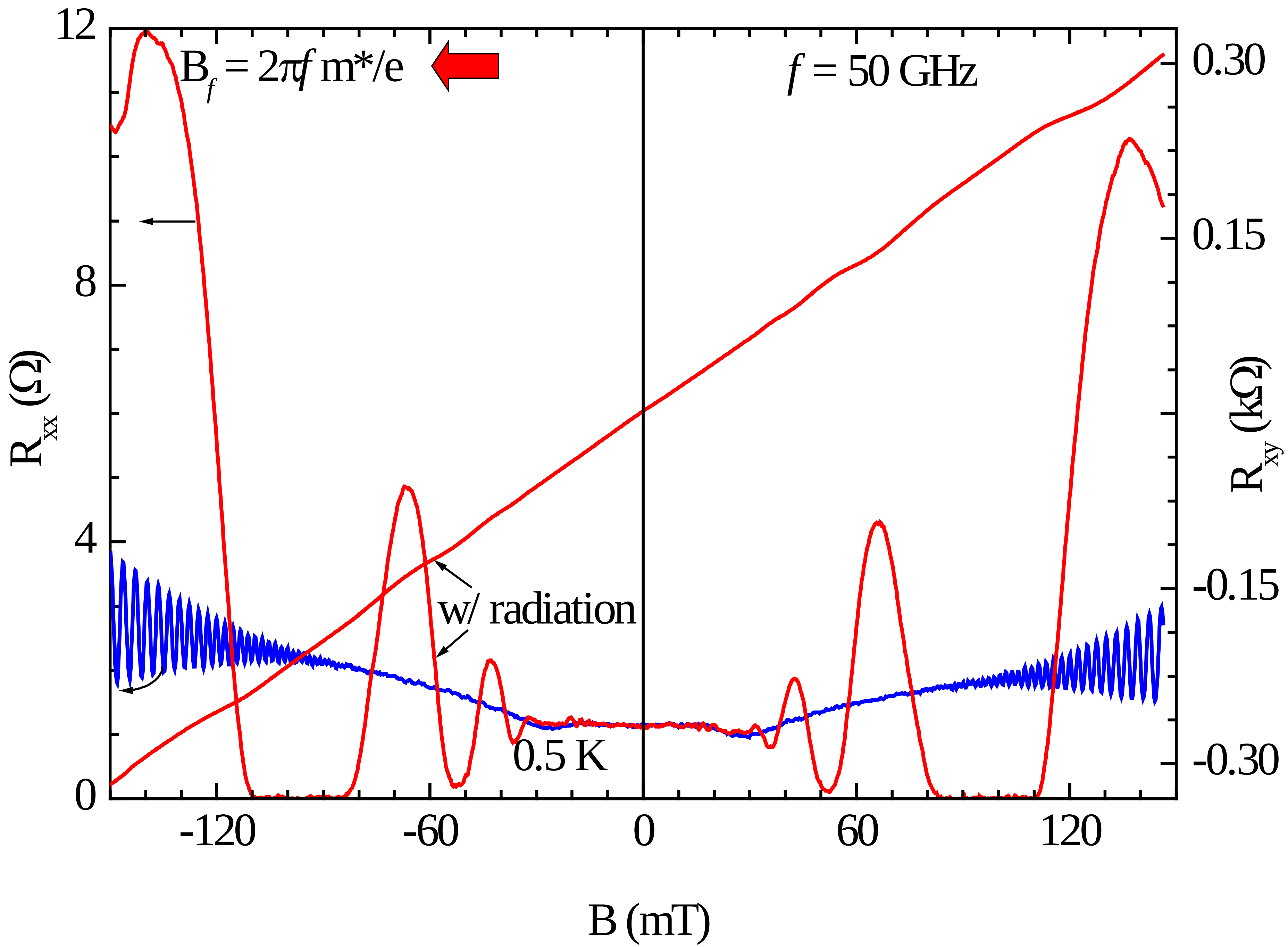
Low B transport: GaAs/AlGaAs heterostructure
12
8
4
0
R_{xx} (Ω)
0.5 K
-120
-60
0
60
120
B (mT)



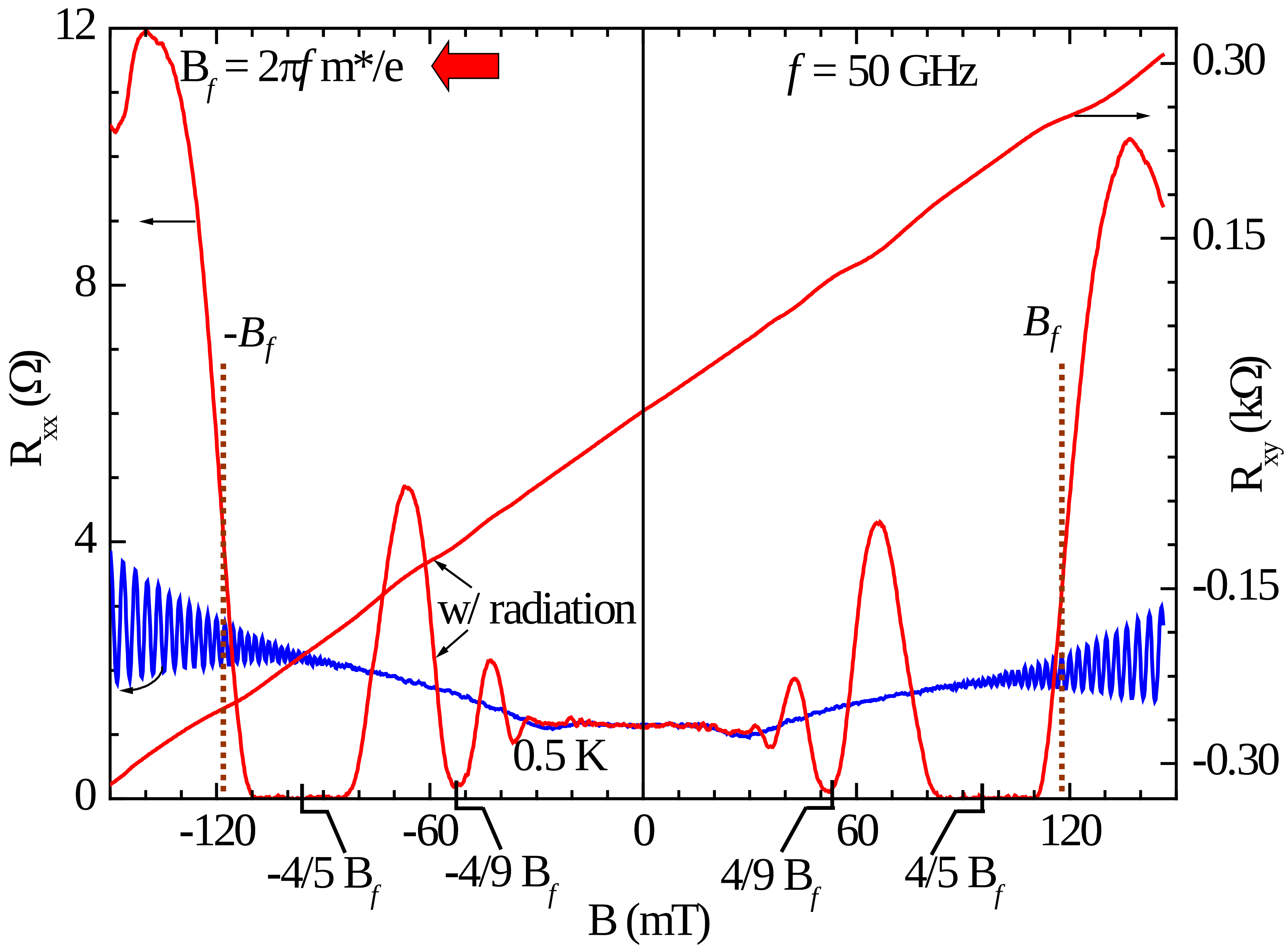
12
8
4
0
-120
-60
0
60
120
R_{xx} (Ω)
B (mT)
f = 50 GHz
0.5 K



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



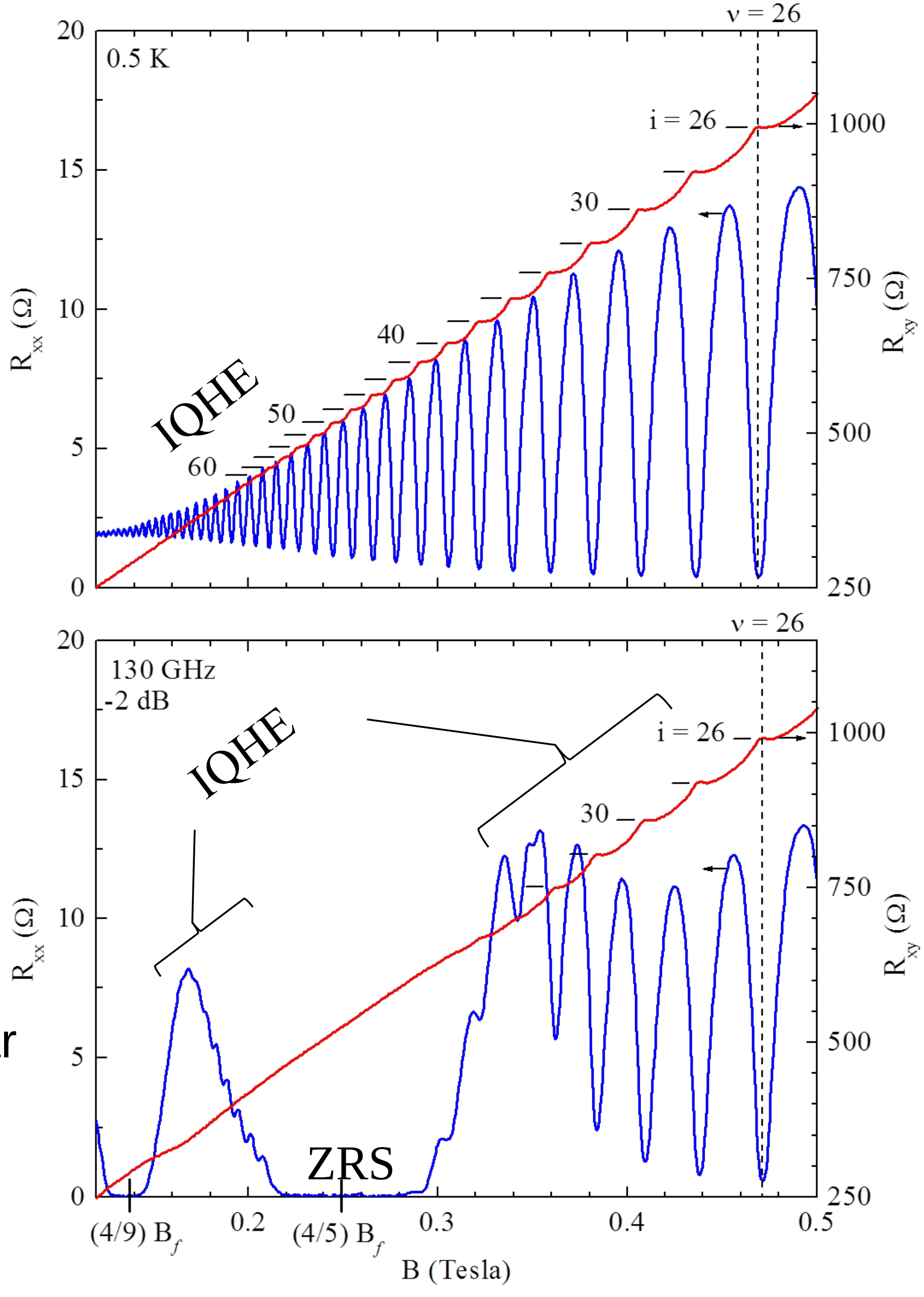
$B_f = 2\pi f\, m^*/e$
f = 50 GHz
w/ radiation
0.5 K
R_{xx} (Ω)
R_{xy} (kΩ)
B (mT)
12
8
4
0
0.30
0.15
-0.15
-0.30
-120
-60
0
60
120



$B_f = 2\pi f\, m^*/e$
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
0
4
8
12
-120
-60
0
60
120
0.30
0.15
-0.15
-0.30

Other interesting experimental features

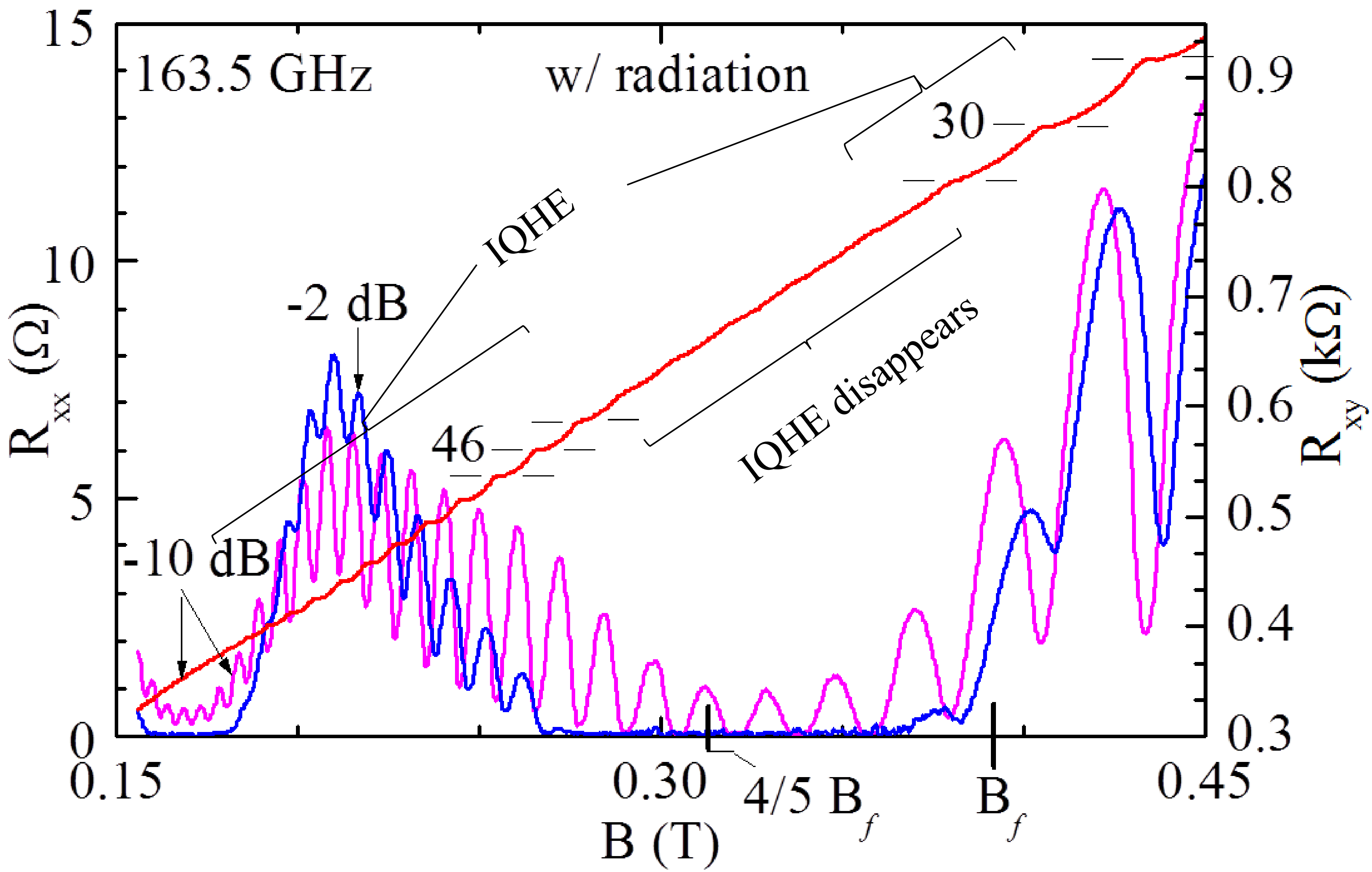
dark



w/ microwaves
Plateaus disappear
over ZRS

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

Re-entrant IQHE under microwave excitation



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

Questions:

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

Theories for the radiation-induced magnetoresistance oscillations

- displacement theory: microwaves modify impurity scattering: $\sigma_{ph}^{(1)}$

  T-independent

  Ryzhii … ’03, **Durst** et al., PRL ’03

- inelastic theory: microwaves change the distribution function: $\sigma_{ph}^{(2)}$

  $\Rightarrow \propto \tau_{in}$, strongly T-dependent

  Dmitriev et al., Dorozhkin

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

- radiation-driven electron orbit model: $\sigma_p^{(3)}$

  exact treatment of harmonic oscillator under microwave photo-excitation + perturbative treatment of elastic scattering:

  Inarrea and Platero, PRL ‘05

- non-parabolicity model: $\sigma_p^{(4)}$

  photo-conductivity arises for linearly polarized radiation in a non-parabolic system

  Koulakov and Raikh, PRB ’03

- Others: **Shepelyansky, Chepelianskii**, **Rivera & Schulz**, **Mikhailov** etc.

Common characteristic of some theories:

- Prediction of negative magnetoresistivity/magnetoconductivity

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

Radiation-Induced Magnetoresistance Oscillations in a 2D Electron Gas

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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

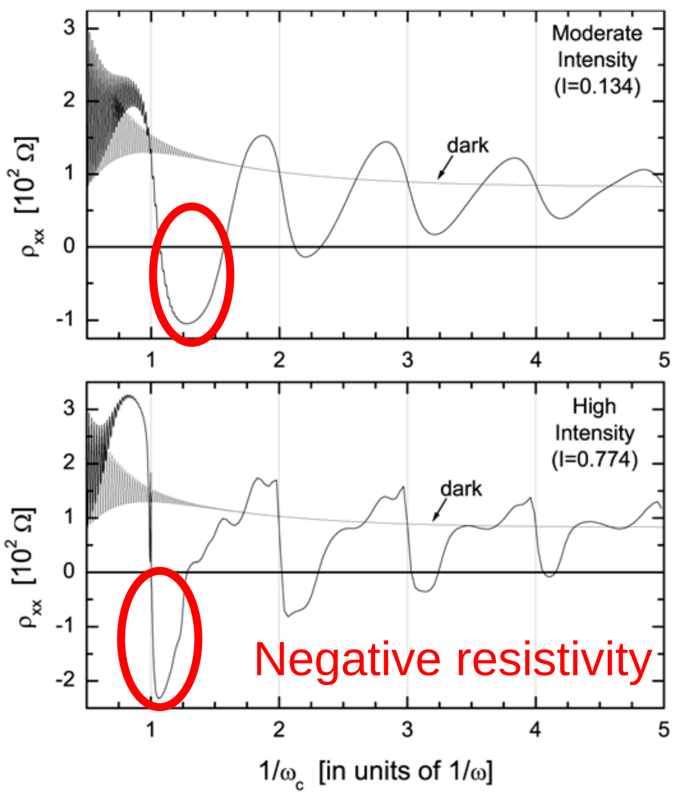

FIG. 3: Calculated longitudinal resistivity. We plot ρ_{xx} vs $1/\omega_c$ at fixed ω for $\mu = 50\omega$, $k_BT = \omega/4$, $= 0.08\omega$, and three values of radiation intensity (in units of $m^*\omega^3$): $I = 0$ (dark), $I = 0.134$, and $I = 0.774$ (see [10]). For computational purposes, the (... above and below ... oscil- lations ...

Displacement model

PHYSICAL REVIEW B 71, 115316 (2005)

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

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(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

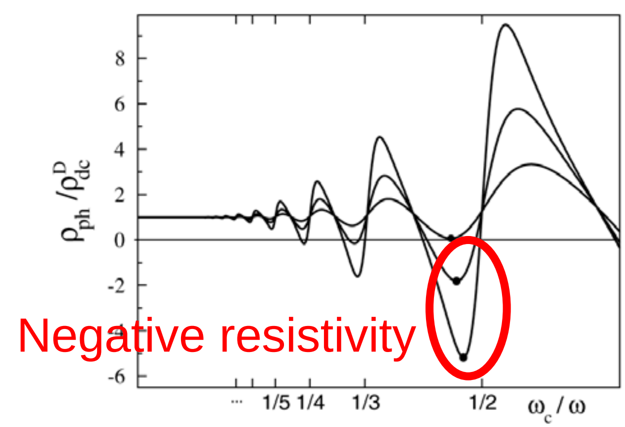

FIG. 1. Photoresistivity (normalized to the dark Drude value) for overlapping Landau levels vs ω_c/ω at fixed $\omega\tau_q = 2\pi$. The curves correspond to different levels of microwave power $\mathcal{P}_\omega^{(0)} = \{0.24, 0.8, 2.4\}$. Nonlinear $I - V$ characteristics at the marked minima are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

Inelastic model

Non parabolicity model for obtaining magneto-resistance oscillations

PHYSICAL REVIEW B **68**, 115324 (2003)

Classical model for the negative dc conductivity of ac-driven two-dimensional electrons near the cyclotron resonance

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Department of Physics, University of Utah, Salt Lake City, Utah 84112, USA
(Received 28 March 2003; revised manuscript received 1 July 2003; published 29 September 2003)

A classical model for dc transport of two-dimensional electrons in a perpendicular magnetic field and under strong irradiation is considered. We demonstrate that, near the cyclotron resonance condition, and for *linear* polarization of the ac field, a strong change of the diagonal component, σ_d, of the dc conductivity occurs in the presence of a *weak* nonparabolicity of the electron spectrum. Small change in the electron effective mass due to irradiation can lead to negative σ_d, while the Hall component of the dc conductivity remains practically unchanged. Within the model considered, the sign of σ_d depends on the relative orientation of the dc and ac fields, the sign of the detuning of the ac frequency from the cyclotron resonance, and the sign of nonparabolic term in the energy spectrum. We also demonstrate that the known phenomenon of the nonparabolicity-induced hysteresis in the cyclotron absorption manifests itself in the dc transport by causing a hysteresis in the magnetic-field dependence of σ_d.

DOI: 10.1103/PhysRevB.68.115324 PACS number(s): 73.43.Cd, 73.50.Pz

Negative magnetoconductivity

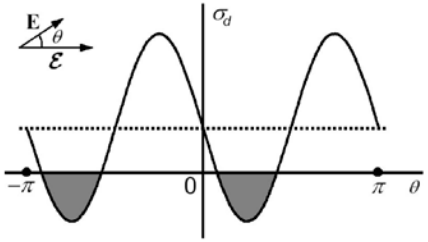

FIG. 1. The diagonal conductivity as a function of the angle θ between ac and dc electric fields, illustrated in the inset. The dashed line shows the dark conductivity. The solid curve is a plot of the diagonal conductivity under irradiation given by Eq. (14). It assumes negative values within the angular intervals shown with gray.

Experiment shows zero resistance…
Theory says negative resistivity…

Question:

How do the negative resistivity/conductivity states transform into experimentally observed zero-resistance states?

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

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(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

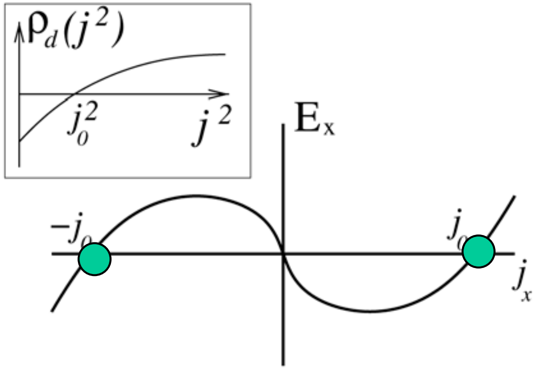


FIG. 1: Conjectured dependence of the dissipative component of the local electric field E_x on the current density j_x. The inset shows the current dependence of the dissipative resistivity.

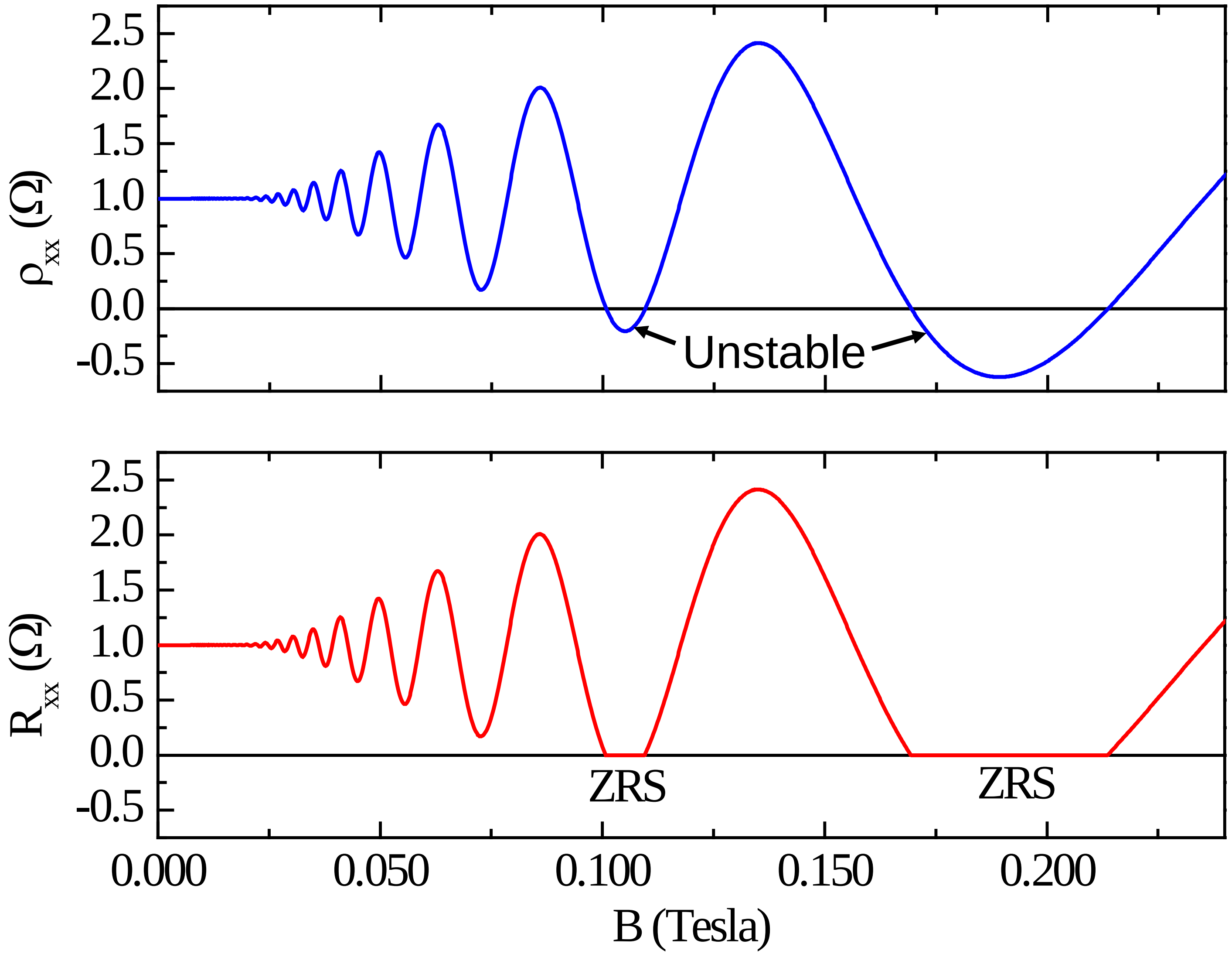
•Negative resistivity is unstable!

•Assume: the resistivity is a function of current

•Currents are set-up such that the resistance vanishes

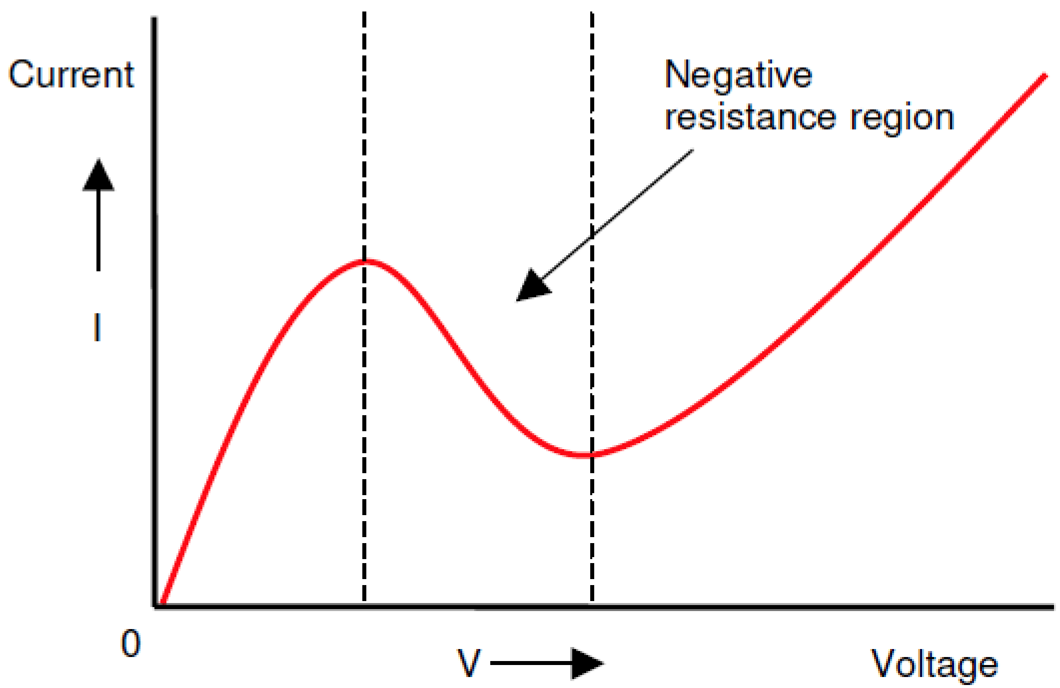
Current domain theory:

Negative resistivity → zero-resistance



Why is negative resistivity/conductivity unstable?

Answer: negative resistivity/conductivity is like negative differential resistivity/conductivity.



Gunn diode device unstable towards oscillations

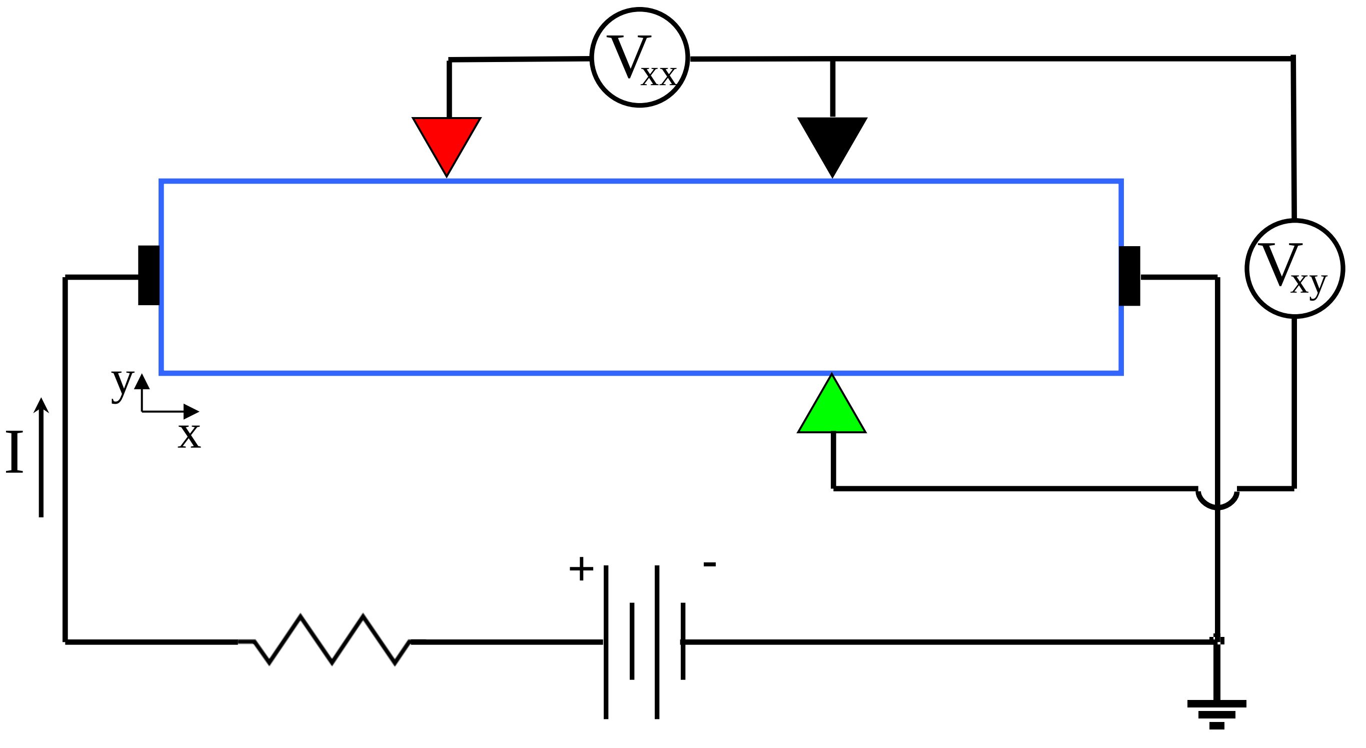
However, negative resisitivity/conductivity in the presence of a magnetic field is not the same as negative resistivity / conductivity at B=0

Due to huge Hall effect in high mobility GaAs/AlGaAs

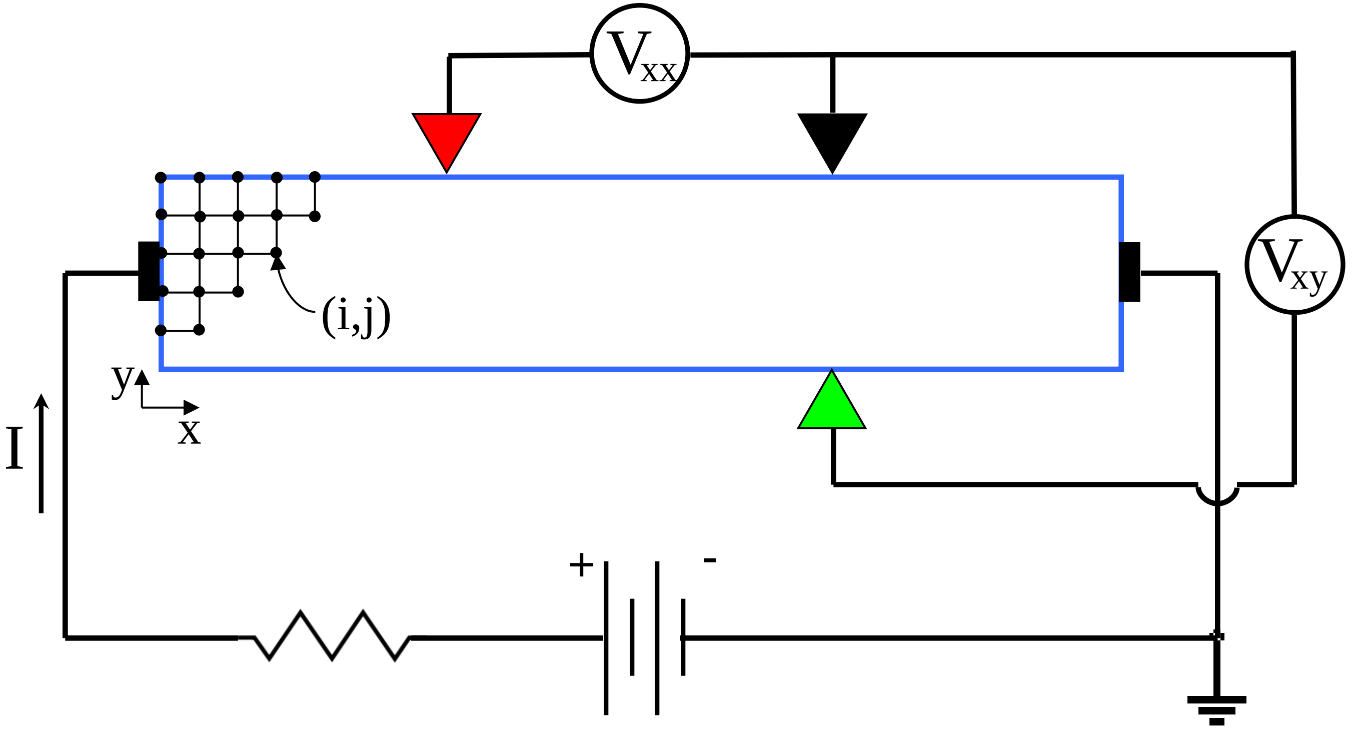
Negative magnetoresistivity/conductivity has not been encountered before by experiment

→signature of the negative magnetoresistivity / conductivity state is unknown

Measurement configuration



Measurement configuration



Simulate potential distribution within a Hall bar device

Simulation

$$\nabla . \mathbf{J} = 0$$

$$\mathbf{J} = \underline{\sigma}\, \mathbf{E}$$

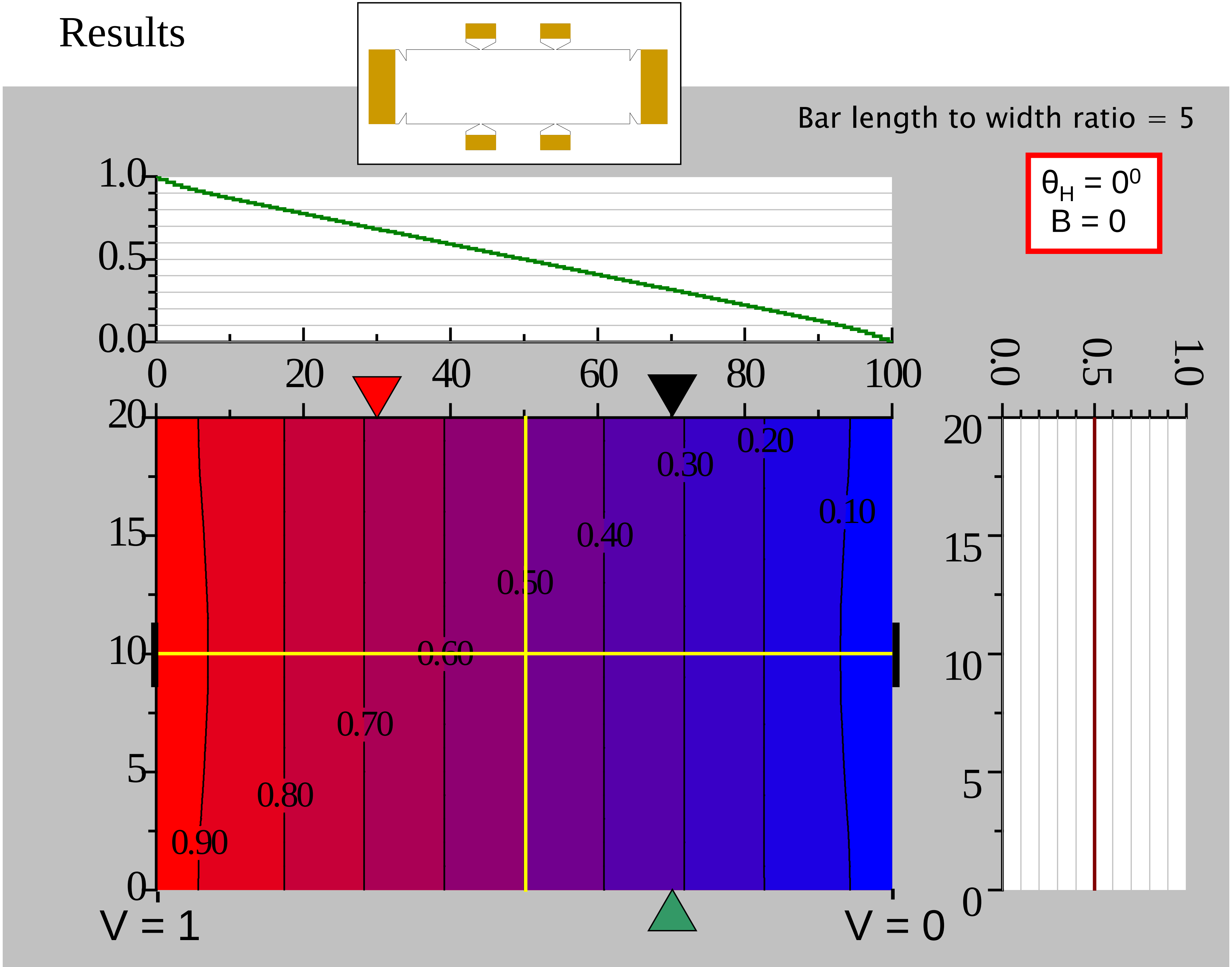
$\underline{\sigma}$ = 2D conductivity tensor

•Solution of laplace equation in finite difference form

•Boundary condition: current injected at the current contacts restricted to flow within conductor

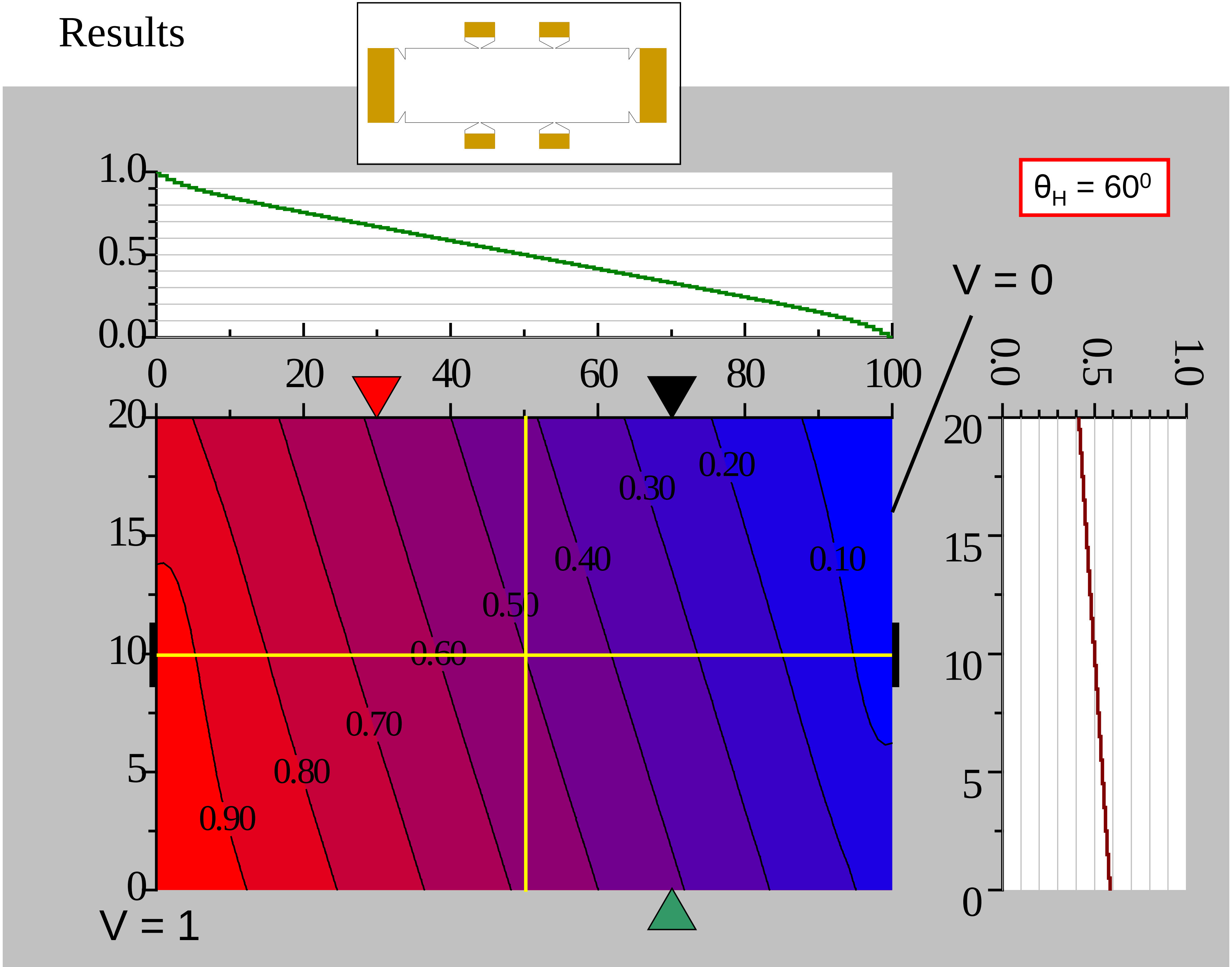
Influential parameter in simulations is the Hall angle
$\tan \theta_H = \sigma_{xy}/\sigma_{xx}$

Results



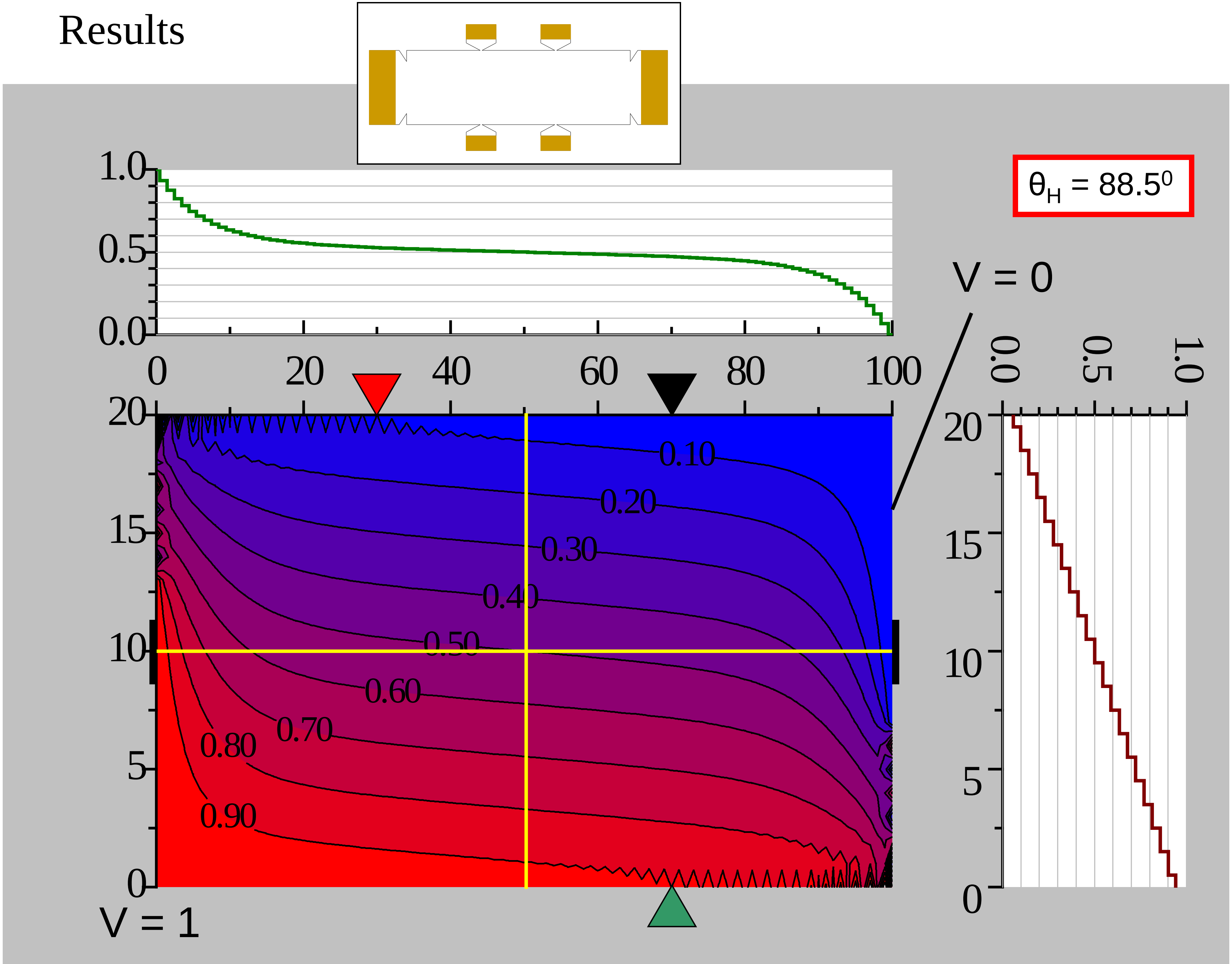
Bar length to width ratio = 5
θH = 0⁰
B = 0
1.0
0.5
0.0
0
20
40
60
80
100
20
15
10
5
0
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
V = 1
V = 0

Results



θH = 60⁰
V = 0
V = 1
1.0
0.5
0.0
0
20
40
60
80
100
15
10
5
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10

Results



θH = 88.5⁰
V = 0
V = 1
1.0
0.5
0.0
0
20
40
60
80
100
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
20
15
10
5
0
0.0
0.5
1.0

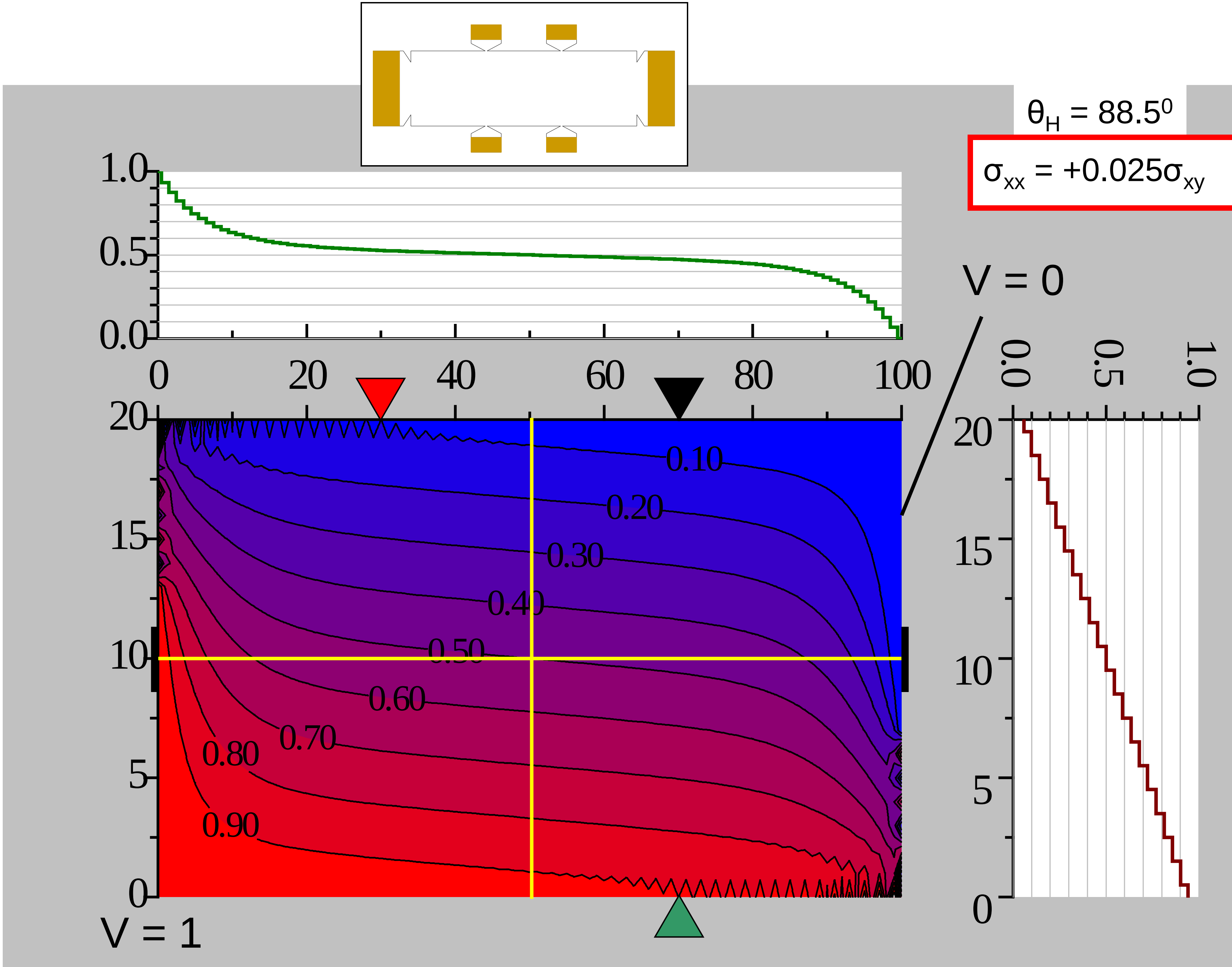
How to simulate the negative conductivity state?

Influential parameter in simulations is the Hall angle
$\tan \theta_H = \sigma_{xy}/\sigma_{xx}$

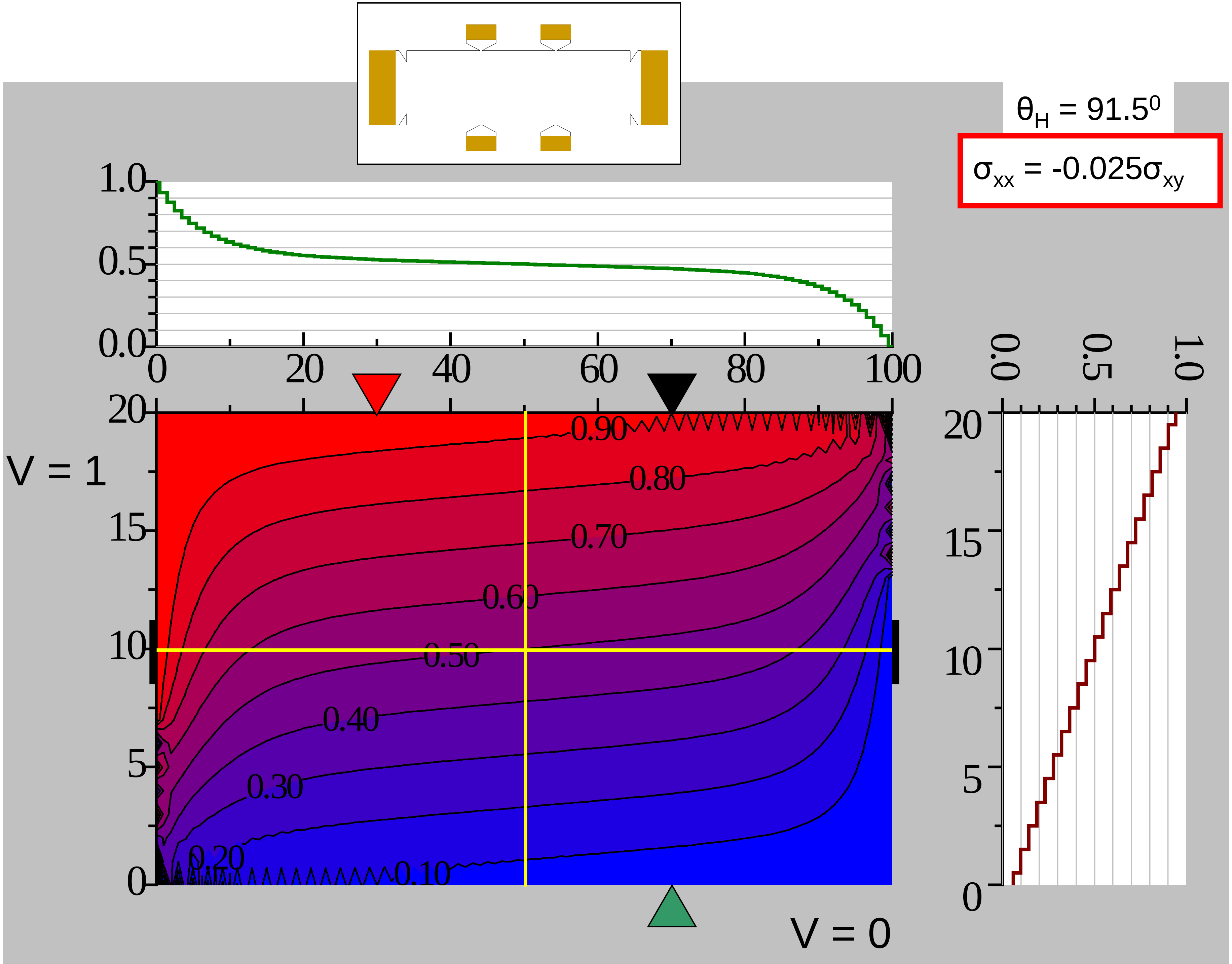
Positive conductivity: $0^0 \leq \theta_H < 90^0$

Negative conductivity: $90^0 \leq \theta_H < 180^0$

→ Compare potential profile for $\theta_H < 90^0$ with potential profile for $\theta_H > 90^0$



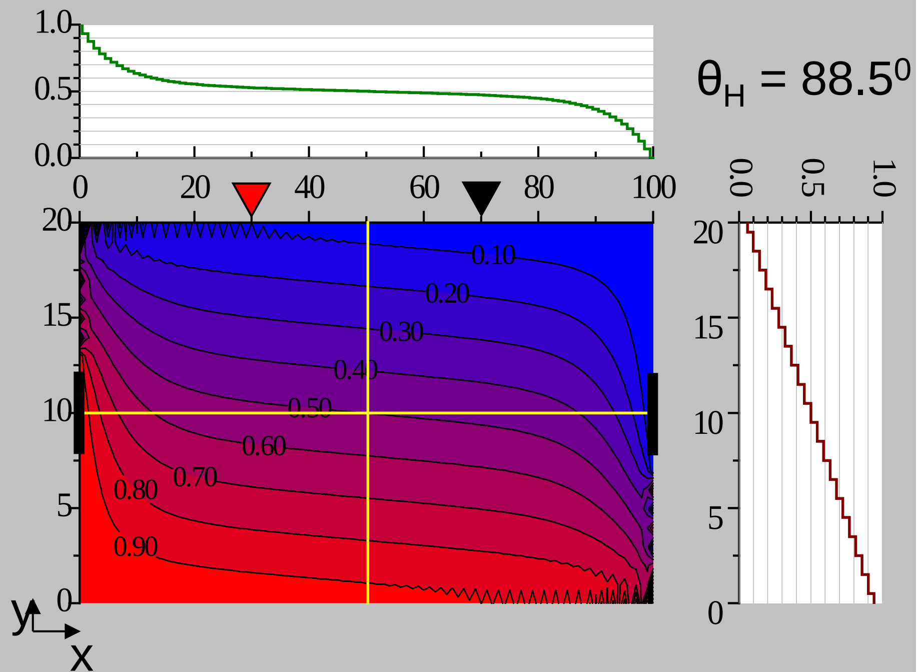
θH = 88.5⁰
σxx = +0.025σxy
V = 0
V = 1
1.0
0.5
0.0
0
20
40
60
80
100
0
5
10
15
20
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90



θH = 91.5⁰
σxx = -0.025σxy
V = 1
V = 0
1.0
0.5
0.0
0
20
40
60
80
100
5
10
15
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10

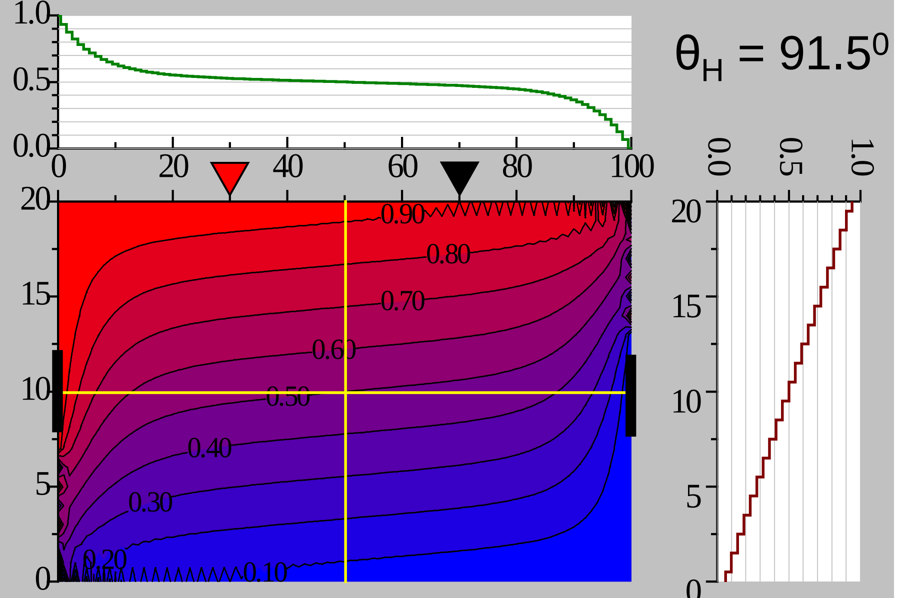
R_{XX} always positive!
Sign reversal in Hall effect

$\theta_H = 88.5^0$



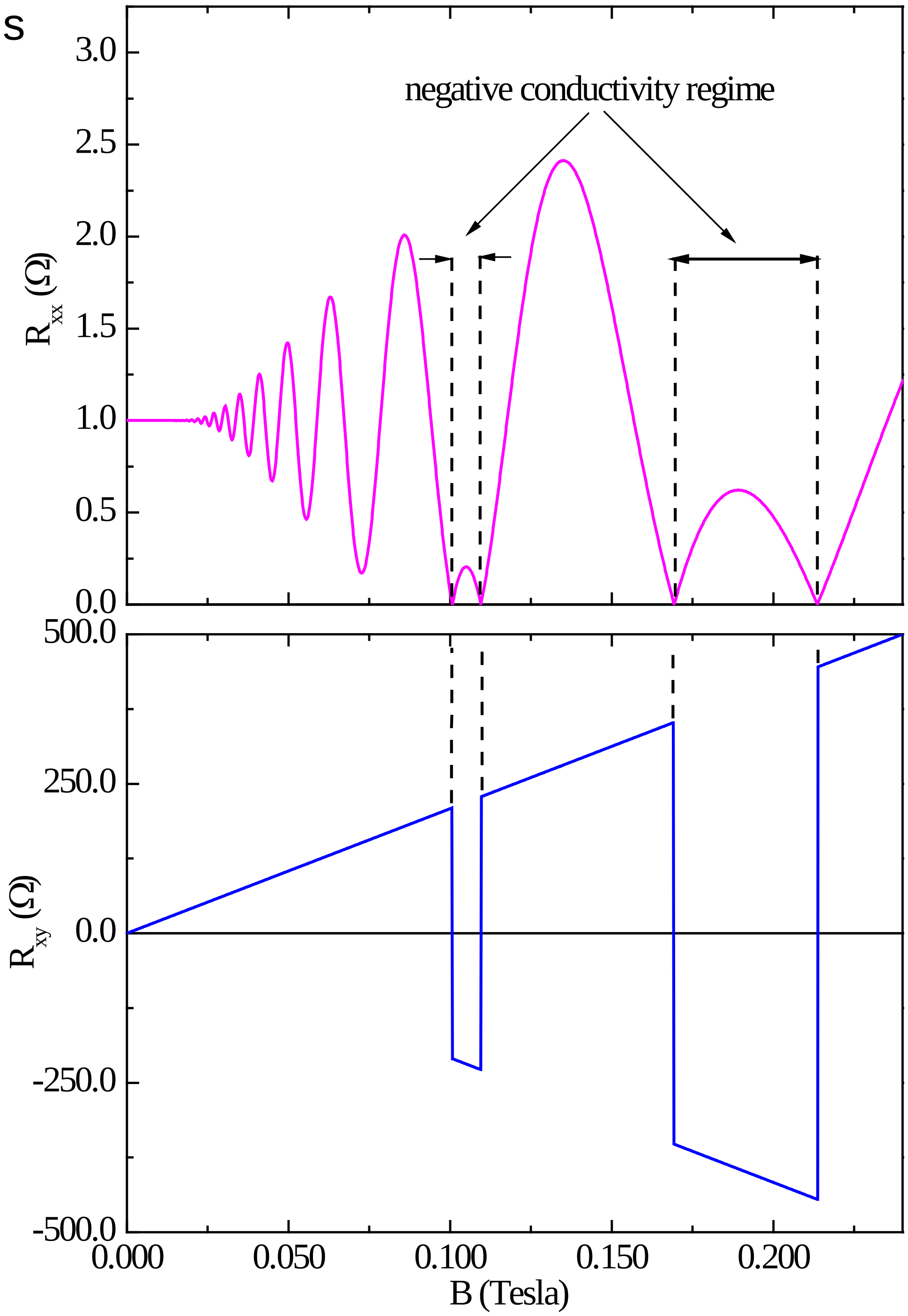
$\sigma_{xx} = 0.025\sigma_{xy}$

$\theta_H = 91.5^0$



$\sigma_{xx} = -0.025\sigma_{xy}$

Transport Expectations for neg. conductivity / resistivity regime:



Summary:

Negative magneto conductivity / resistivity should lead to **positive resistance** along with sign reversal in the Hall effect.

No instability in a positive resistance???

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Part 1 with Dr. Annika Kriisa
Part 2 with Dr. Tianyu Mark Ye

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