SAND2016-6914C

Bloch Oscillations in Two-Dimensional Superlattices

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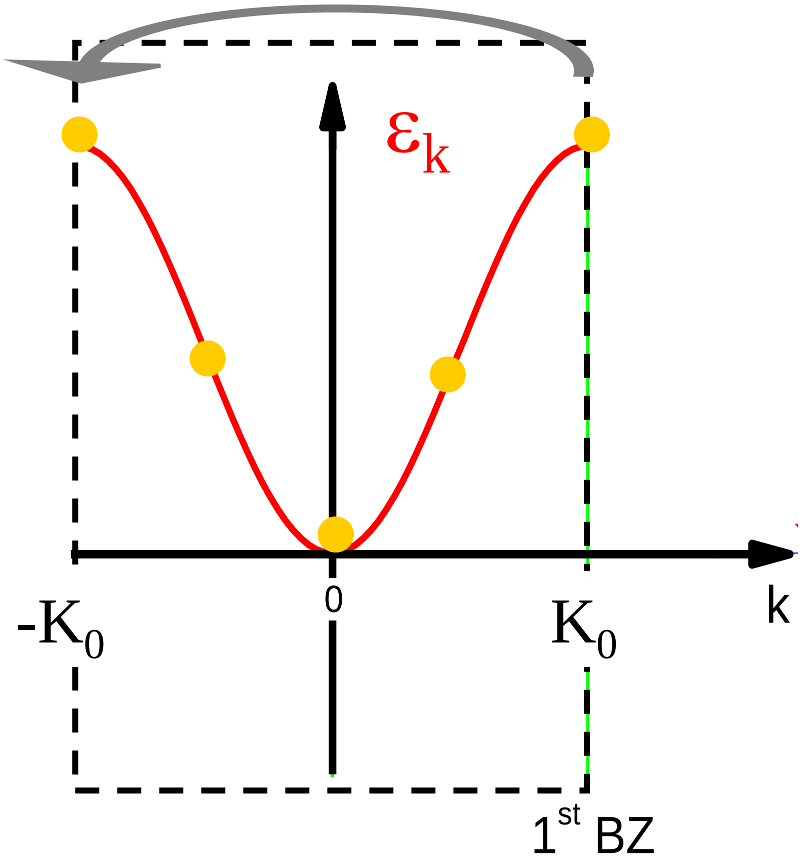
outline

- motivation
- sample fabrication and characterization
- evidence of Bloch oscillations

what is Bloch oscillation?

Bloch, Z. Phys. 1928



$K_0 = \pi/a$, a: lattice constant

Under a DC electric field E

$$F = m \times a = m \times dV/dt = dp/dt$$

$$F = eE,\ p = \hbar k$$

$$\hbar\, dk/dt = eE$$

$$k = eEt/\hbar$$

$$\varepsilon_k \sim 1 - \cos(ak)$$

$$v \sim \partial \varepsilon_k / \partial k \sim \sin(aeEt/\hbar)$$

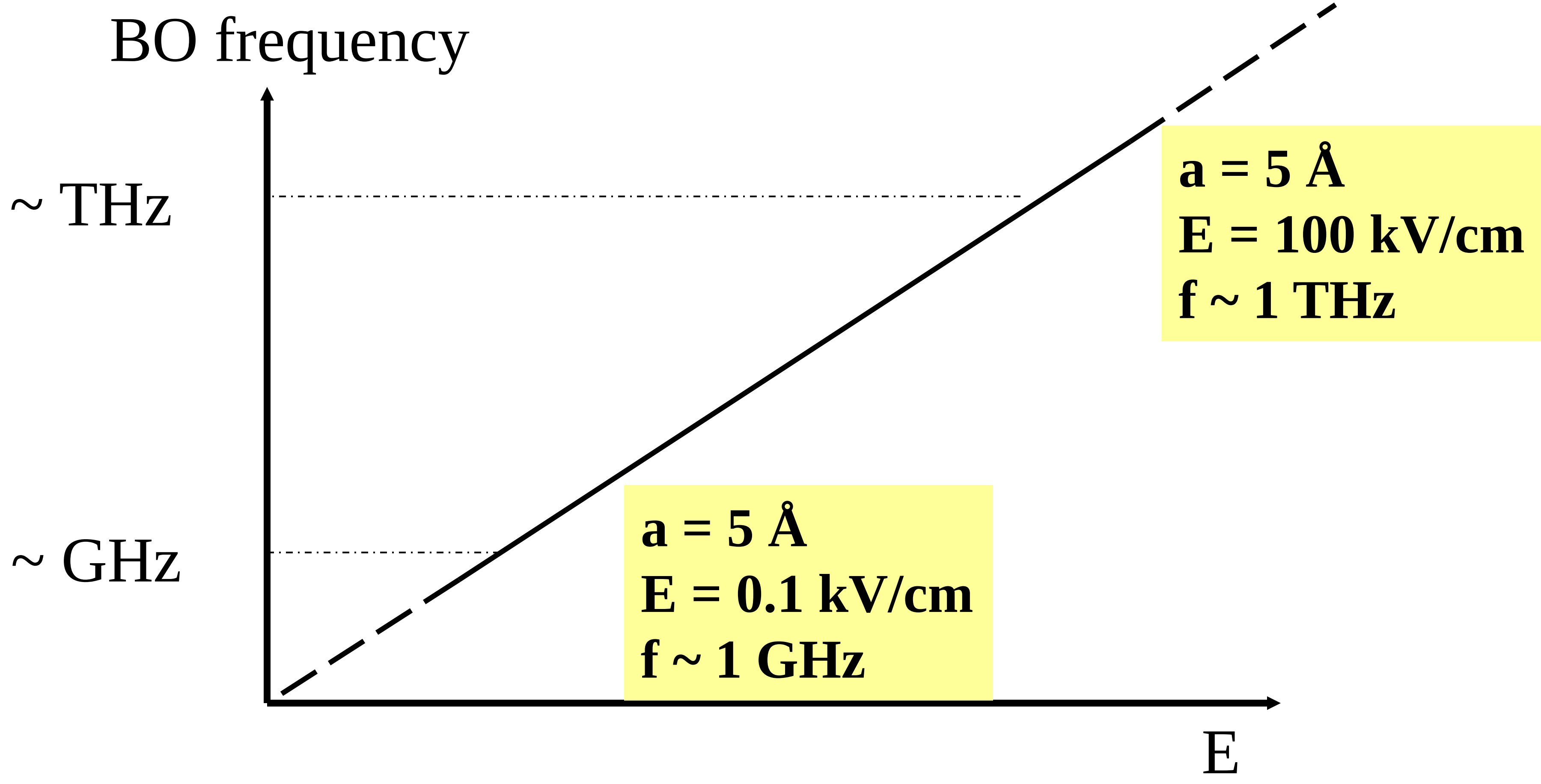
$$r \sim \cos(aeEt/\hbar) = \cos(2\pi f t)$$

$$f = aeE/h$$

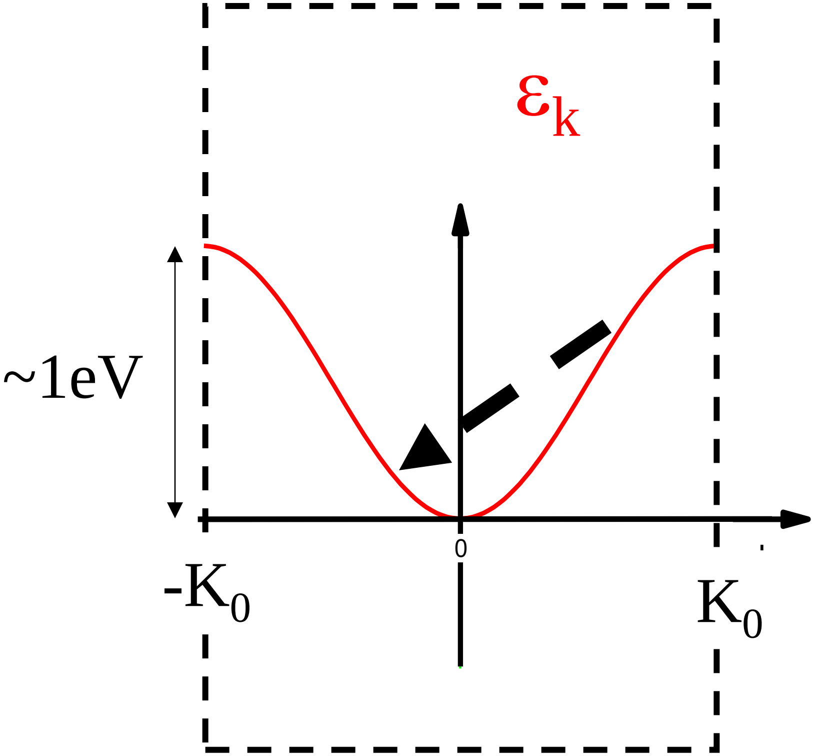
why Bloch oscillations (BO) ?

- THz application – frequency tunable

$$f = aeE/h$$



issues in 3D crystal

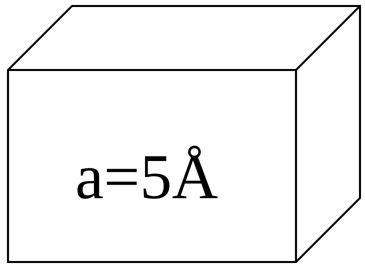


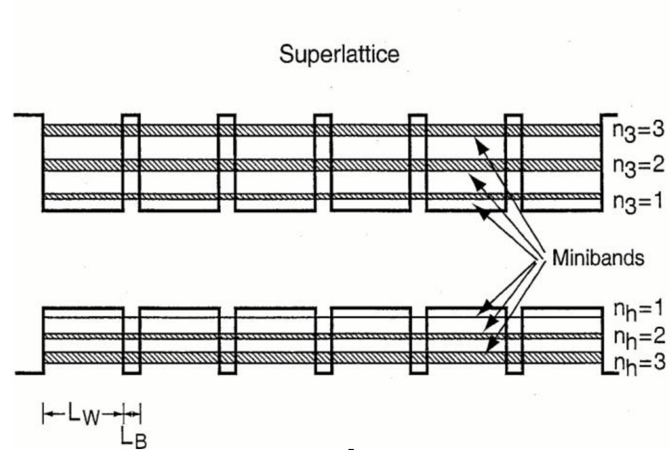
- Very high electric field
- Electron is scattered before it can complete a full oscillation

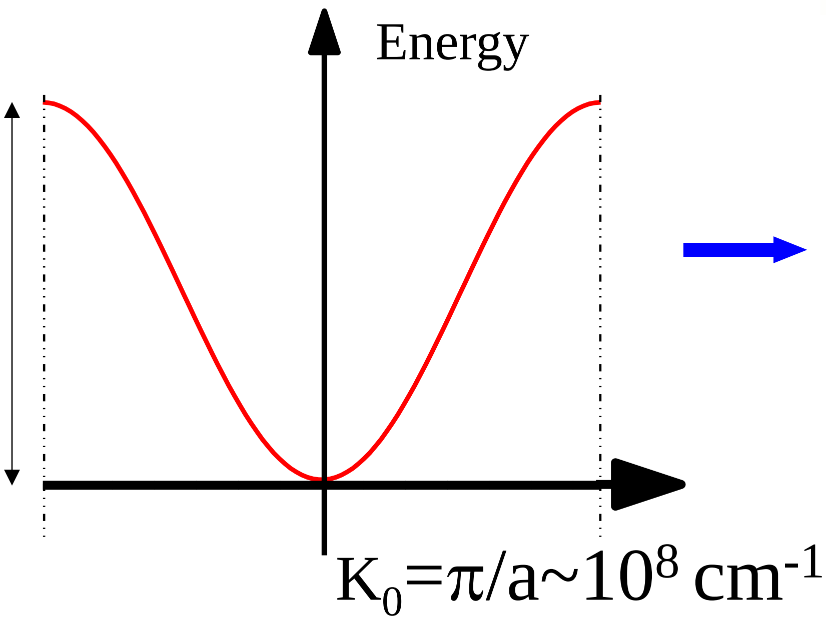
1D vertical superlattice

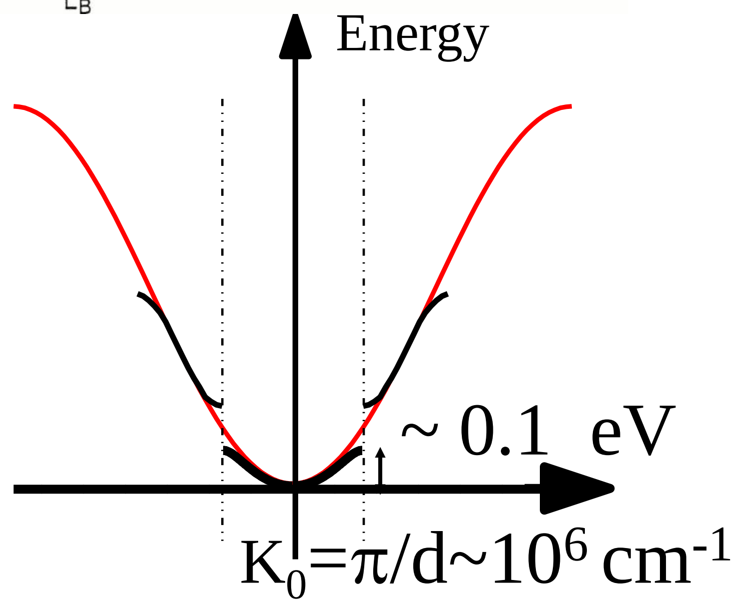
Esaki and Tsu, 1975

3D crystal









issues in 1D vertical superlattice

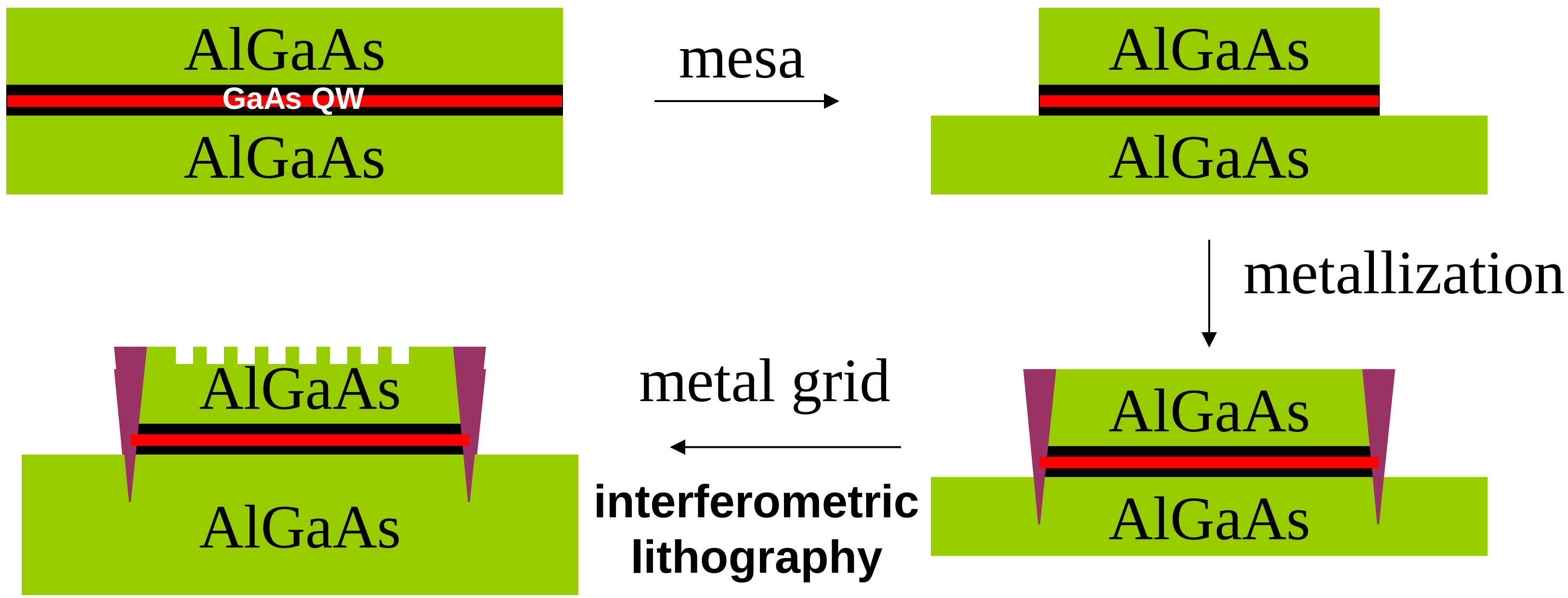
- formation of high electric field domains
- electron – phonon scattering
- impurity scattering
    - surface roughness scattering
- ….

2D quantum "dot" superlattice (QDSL)

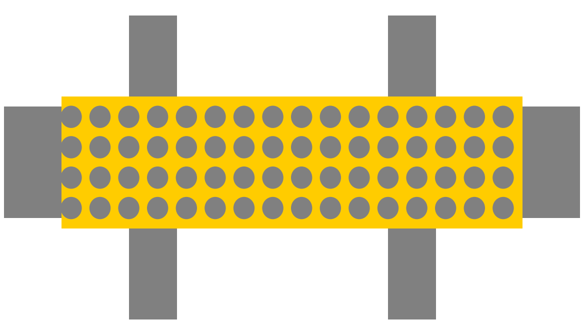
I.A. Dmitriev and R.A. Suris, Semiconductors 35, 212 (2001).

- 3D-quantum confinement, electron-phonon scattering suppressed
- High sample quality, disorder scattering reduced
- 2D dimensionality, formation of electric field domains suppressed
- easy to fabricate, using interferometric lithography

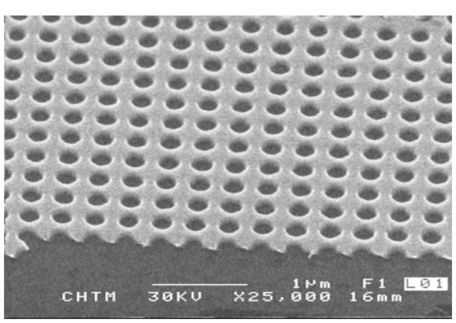
sample fabrication

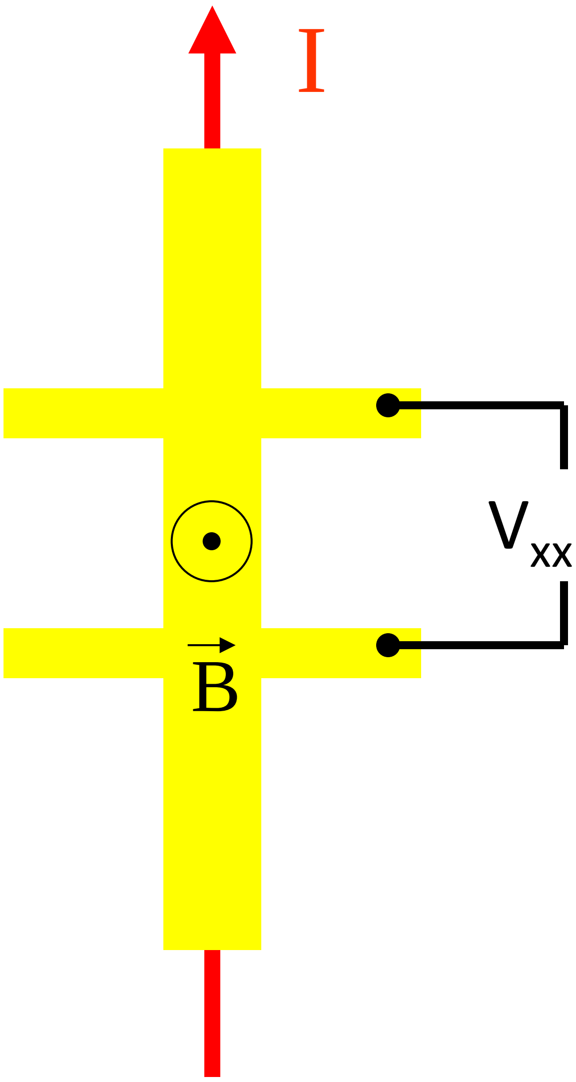


Top view



SEM picture

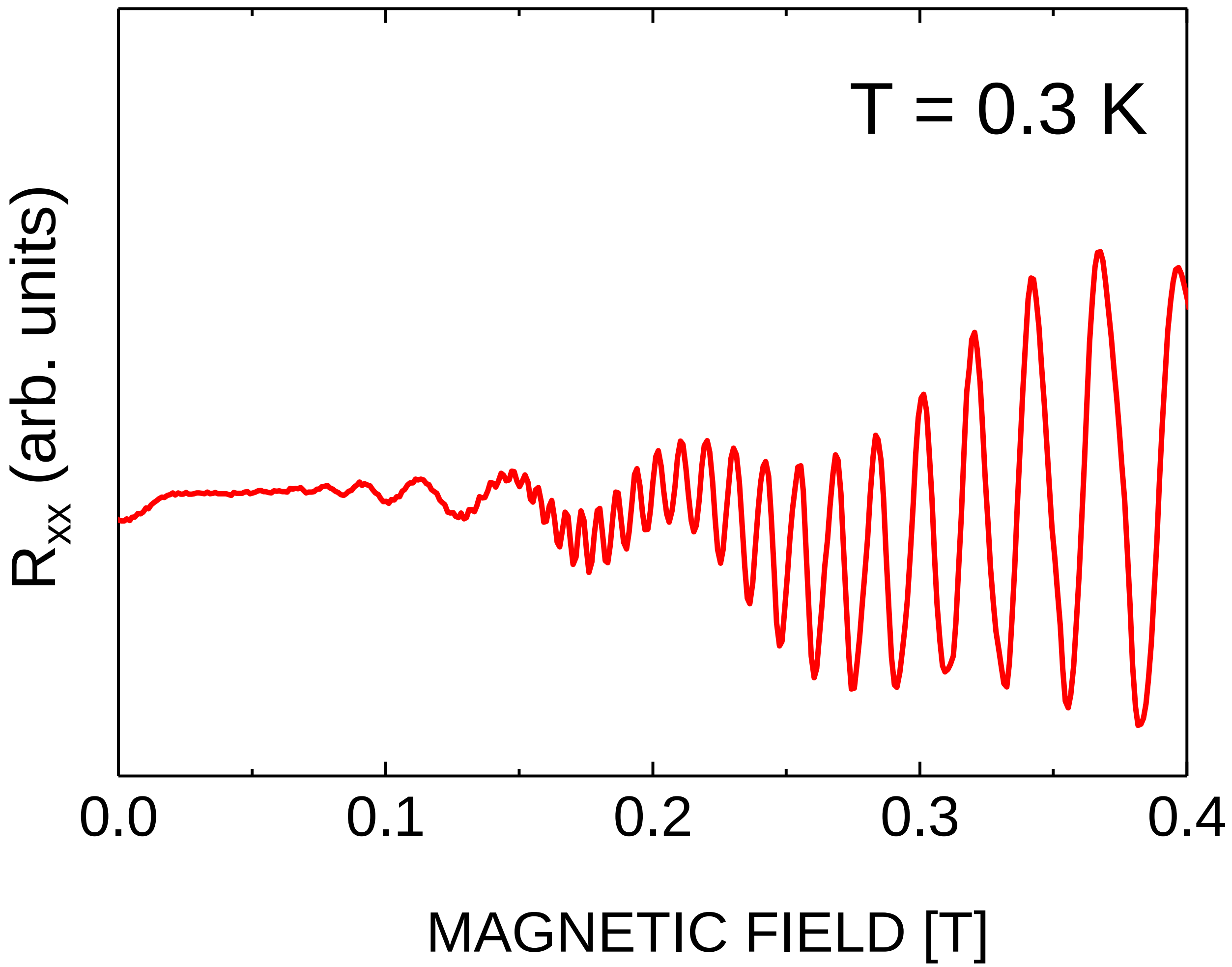


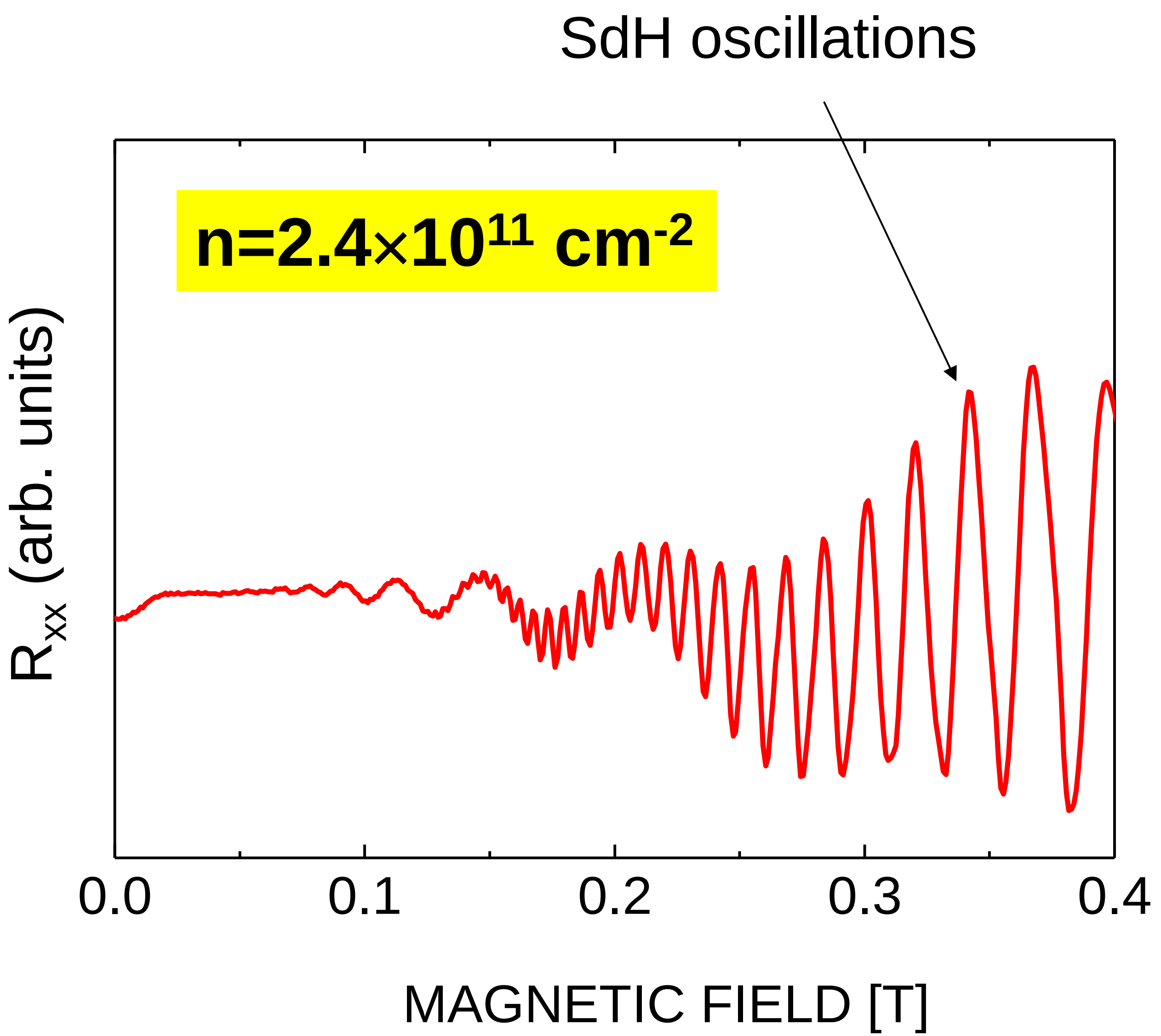


transport coefficients:

$$R_{xx} = V_{xx}/I$$

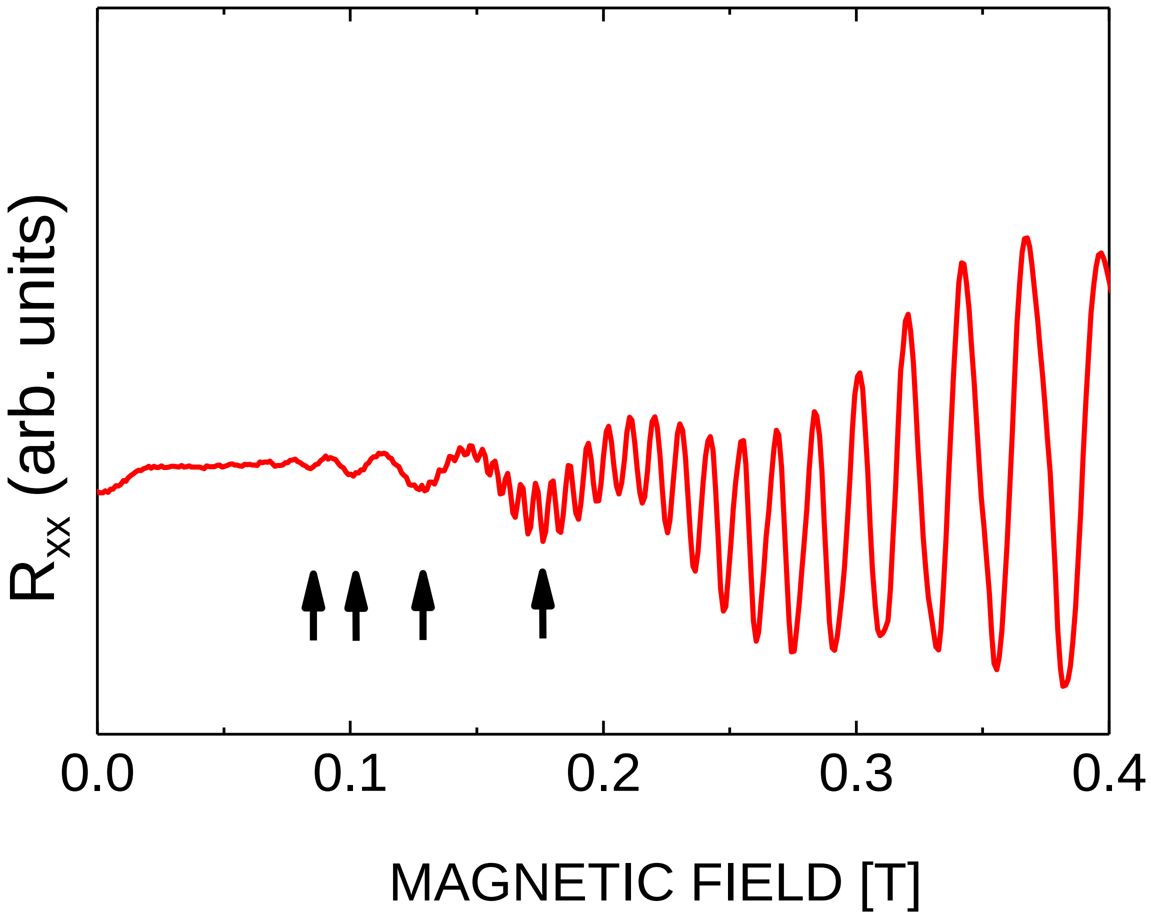
sample characterization – magneto-transport

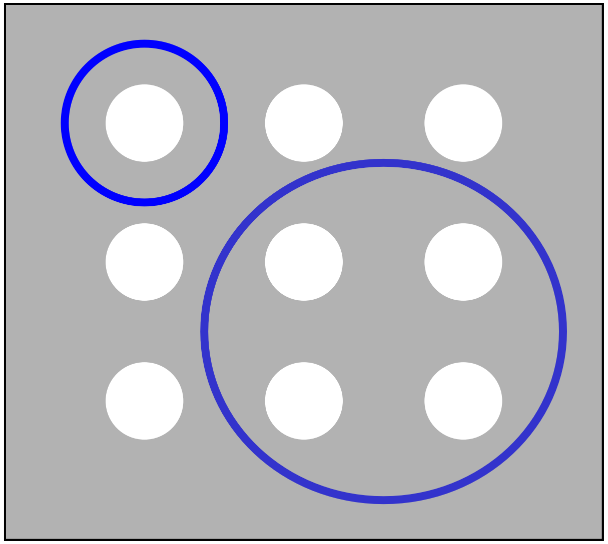


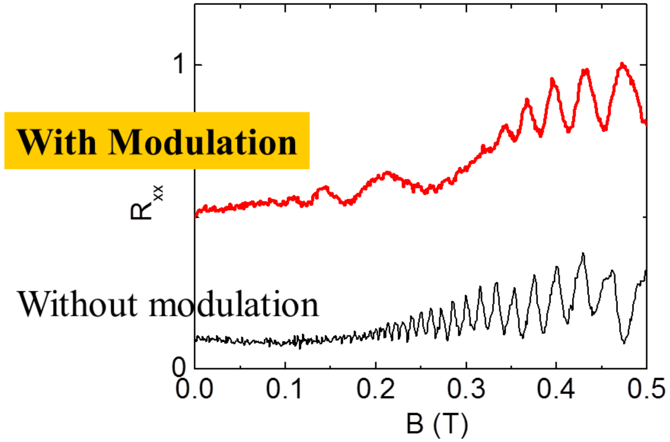


SdH oscillations
n=2.4×10^11 cm^-2
Rxx (arb. units)
0.0
0.1
0.2
0.3
0.4
MAGNETIC FIELD [T]

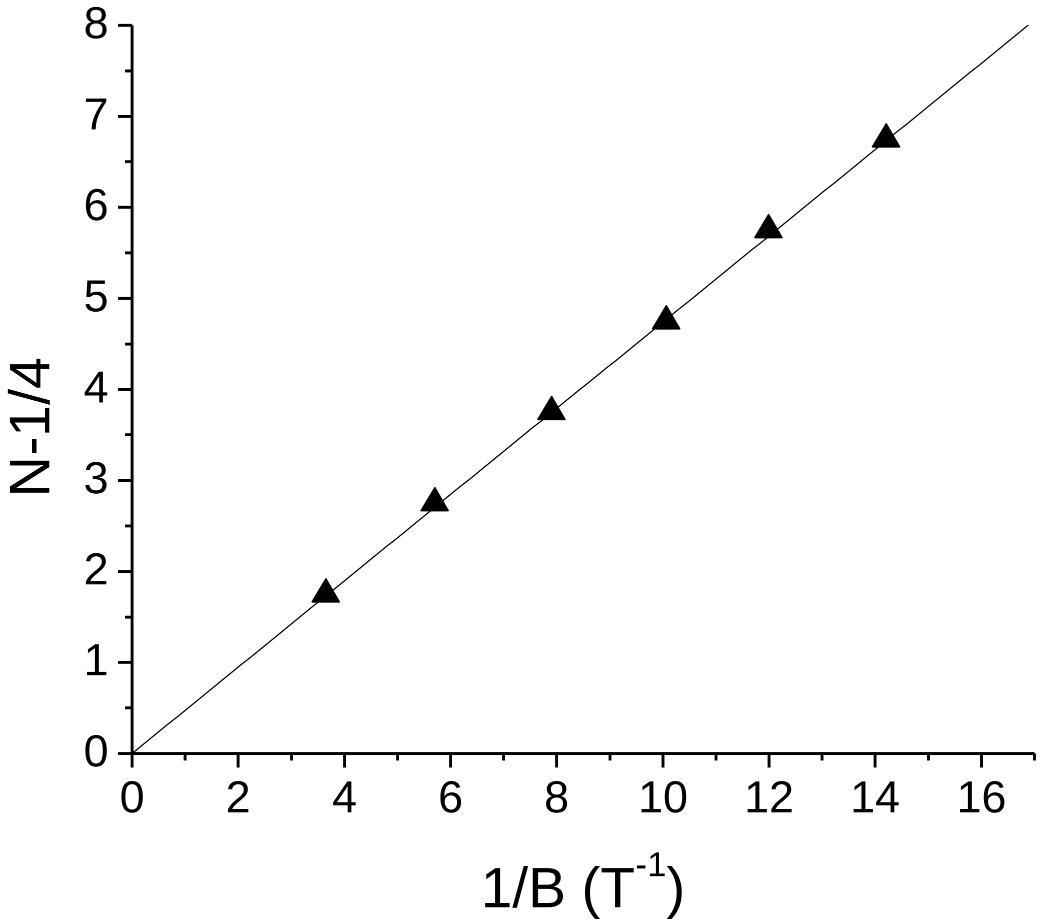
geometric oscillations







Weiss et al, PRL 66, 2790 (1991)



$2R_c/d = N\text{-}1/4$

or

$N\text{-}1/4 = (2\hbar k_F/ed)\times 1/B$

R_c – cyclotron radius

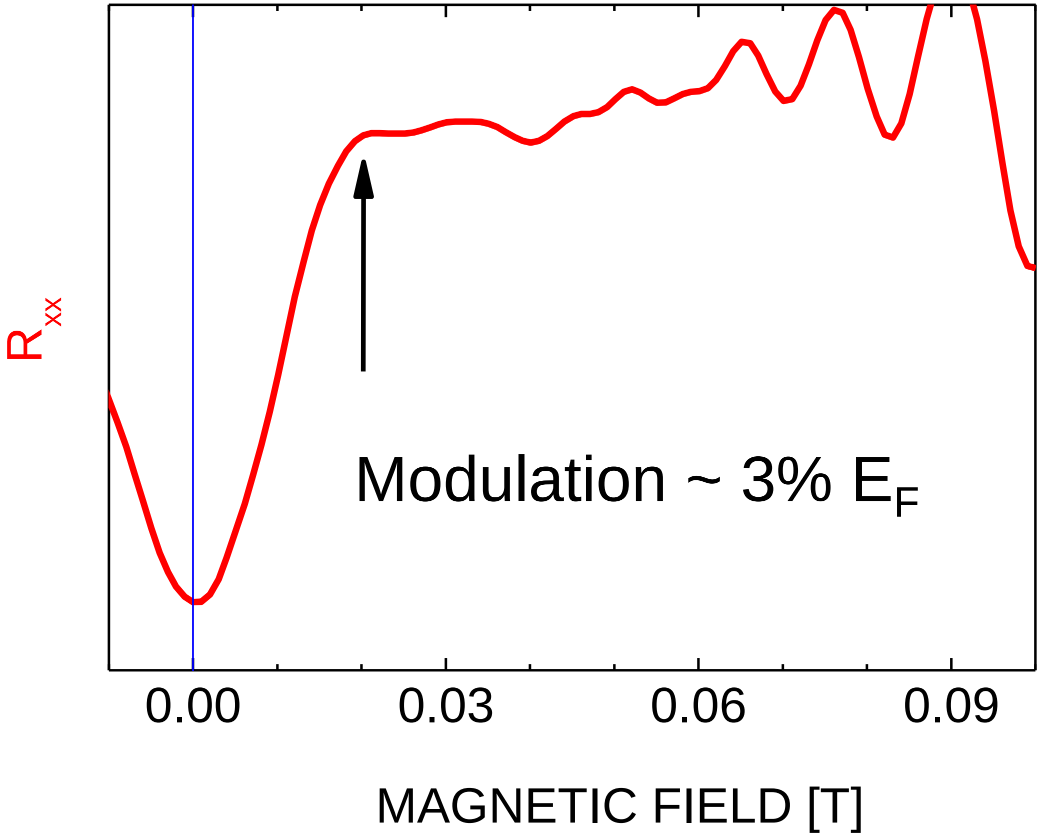
k_F – Fermi wavefactor

From slope,

d ~ 340 nm

Weiss et al, PRL 66, 2790 (1991)

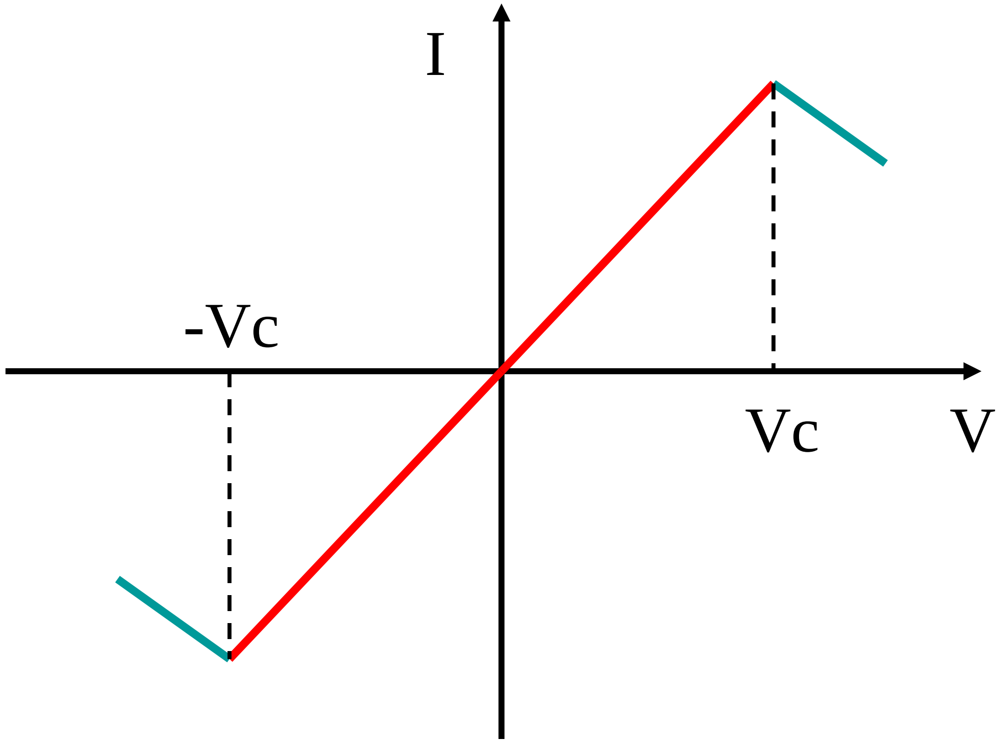
positive magneto-resistance around B = 0



Beton, et al, PRB 42, 9229 (1990)

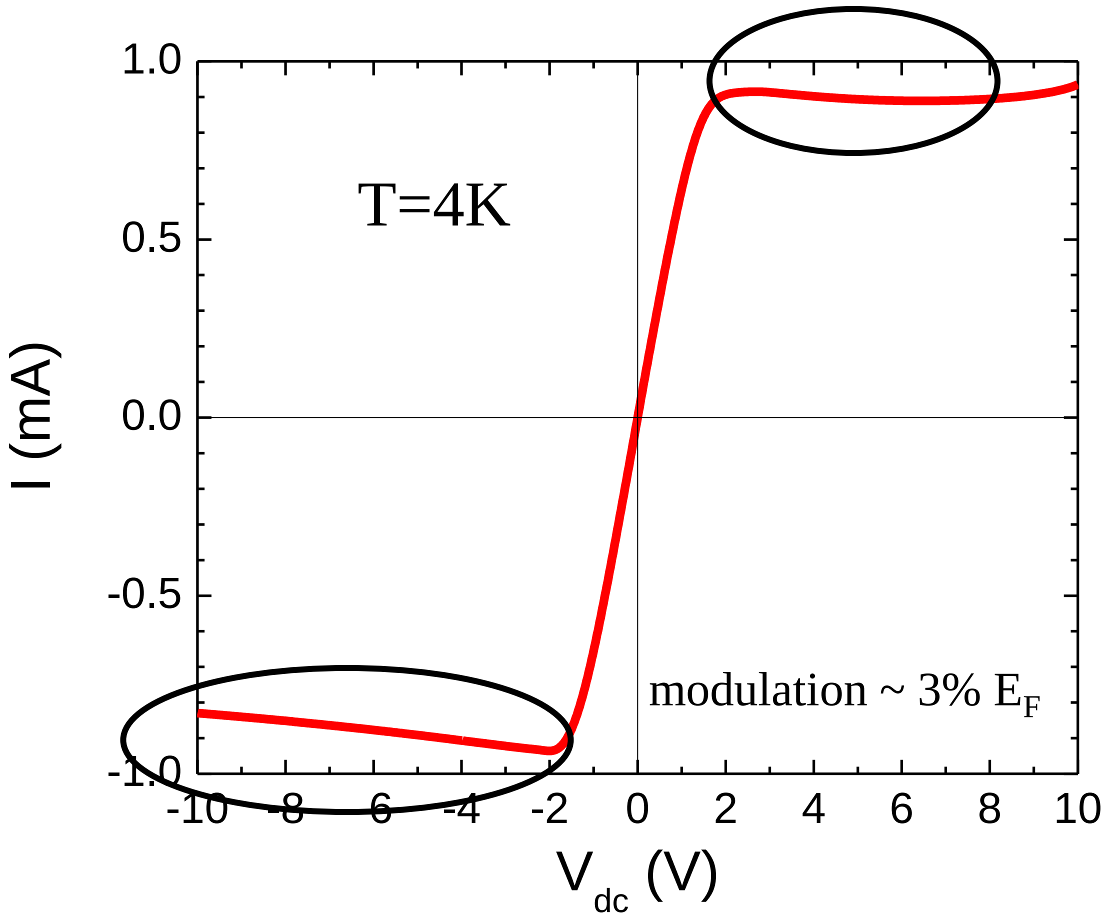
evidence of Bloch oscillations in 2D QDSL

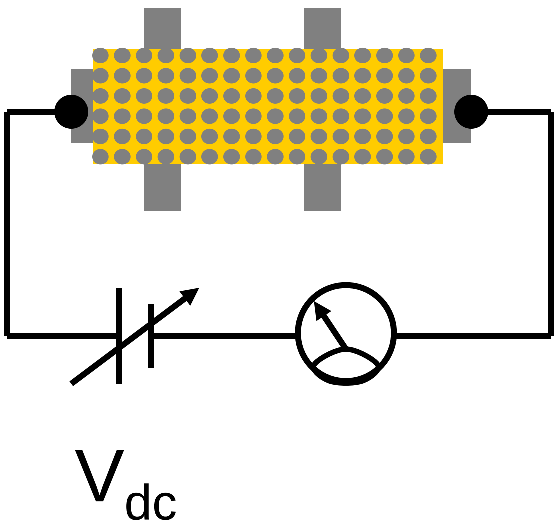
one of the signatures for Bloch oscillations is negative differential conductance (NDC)

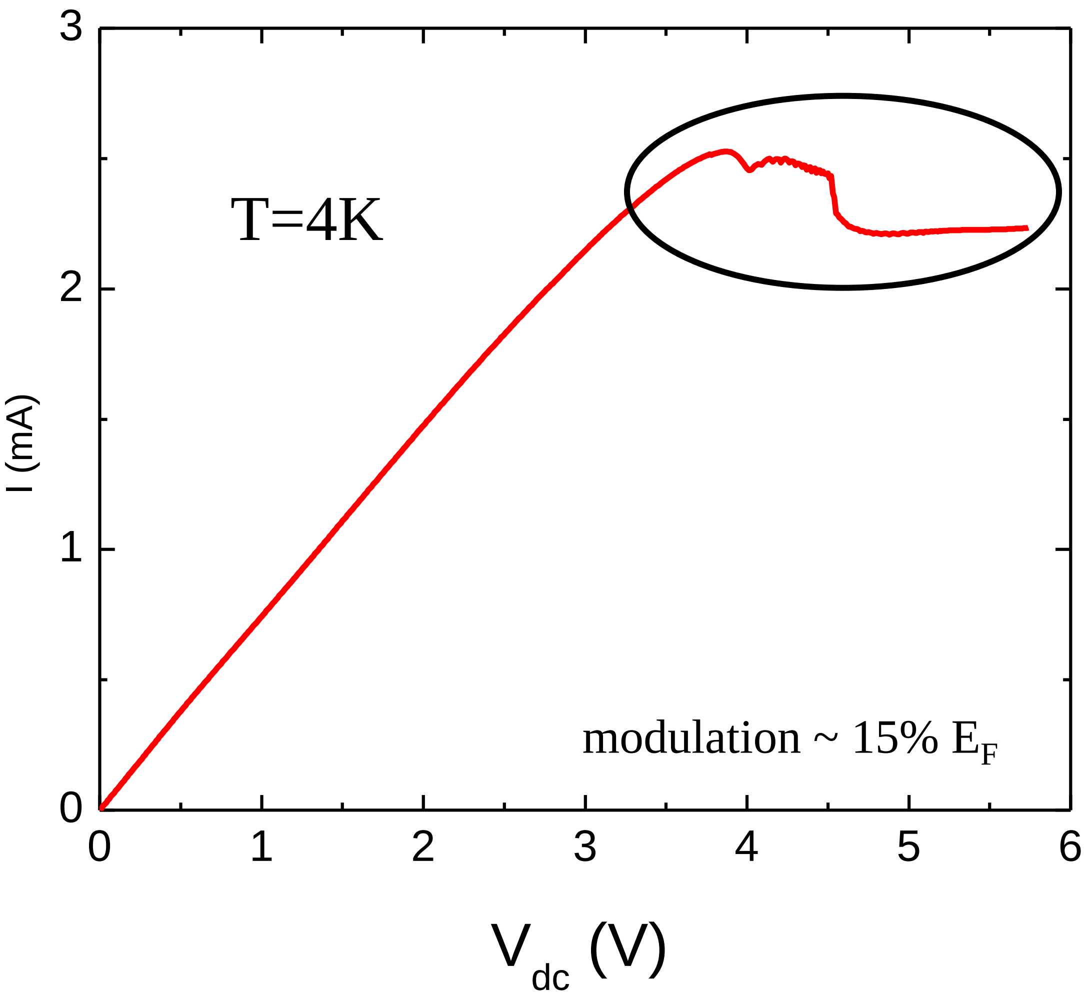


I – V measurement in 2D QDSL

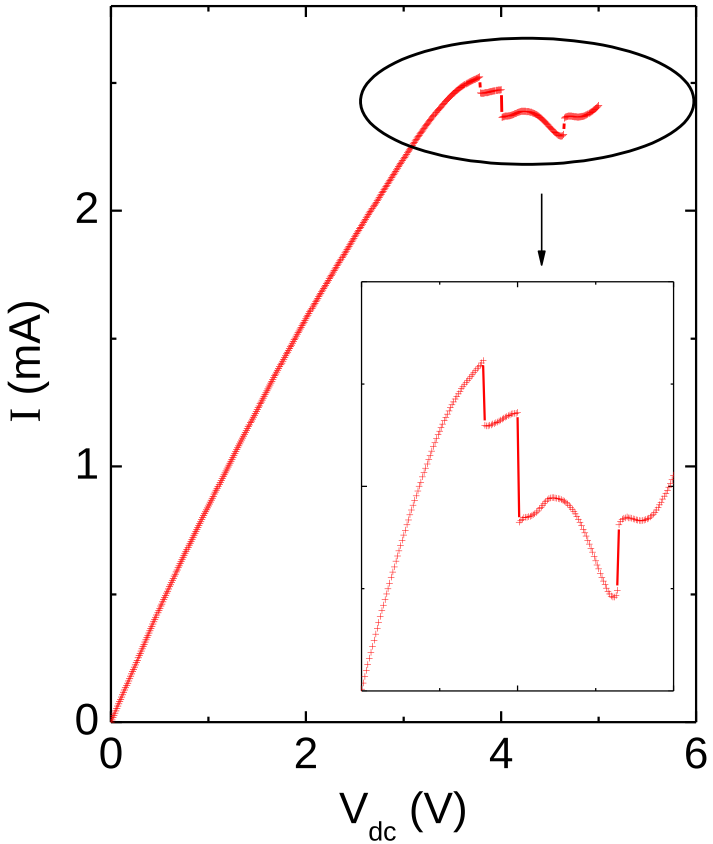
NDC observed





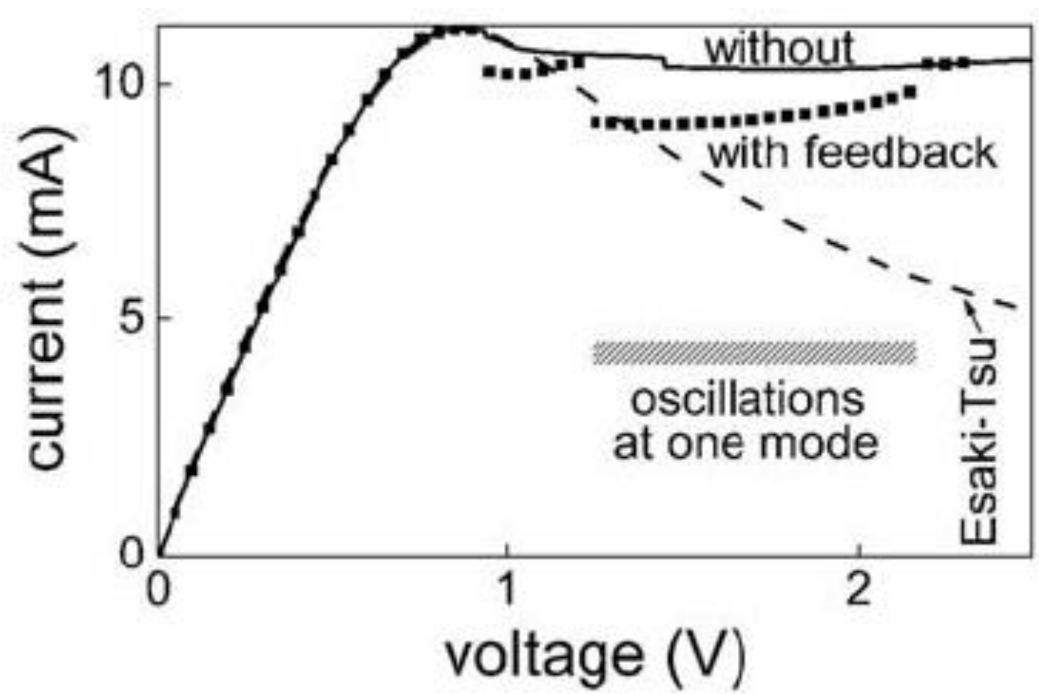

T=4K
modulation ~ 15% E_F
I (mA)
V_dc (V)
0
1
2
3
0
1
2
3
4
5
6

in yet another sample



Similar current jumps were also observed in:

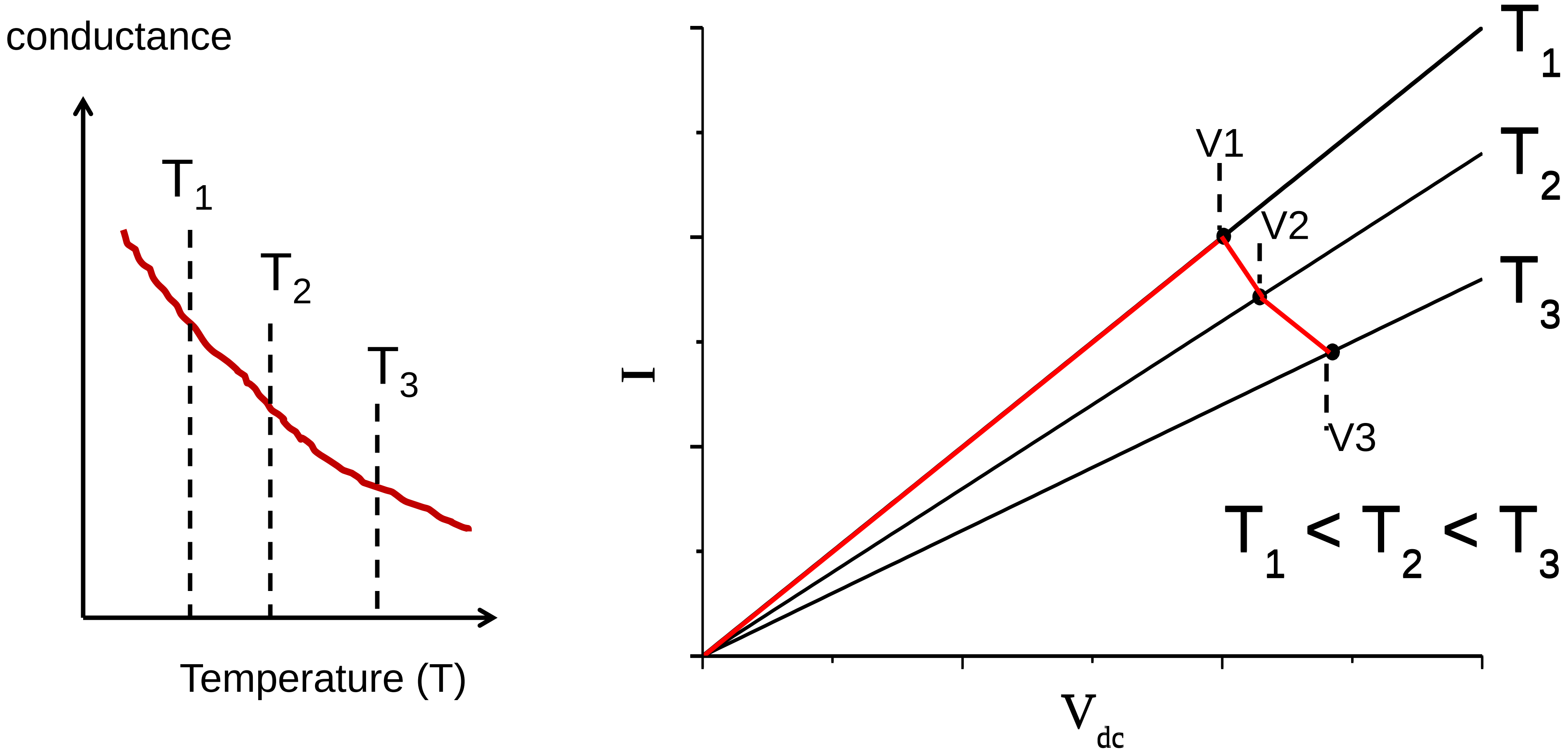
• **GaAs/AlAs 1D superlattices** (Renk et al, 2005)



physical origin of NDC ?

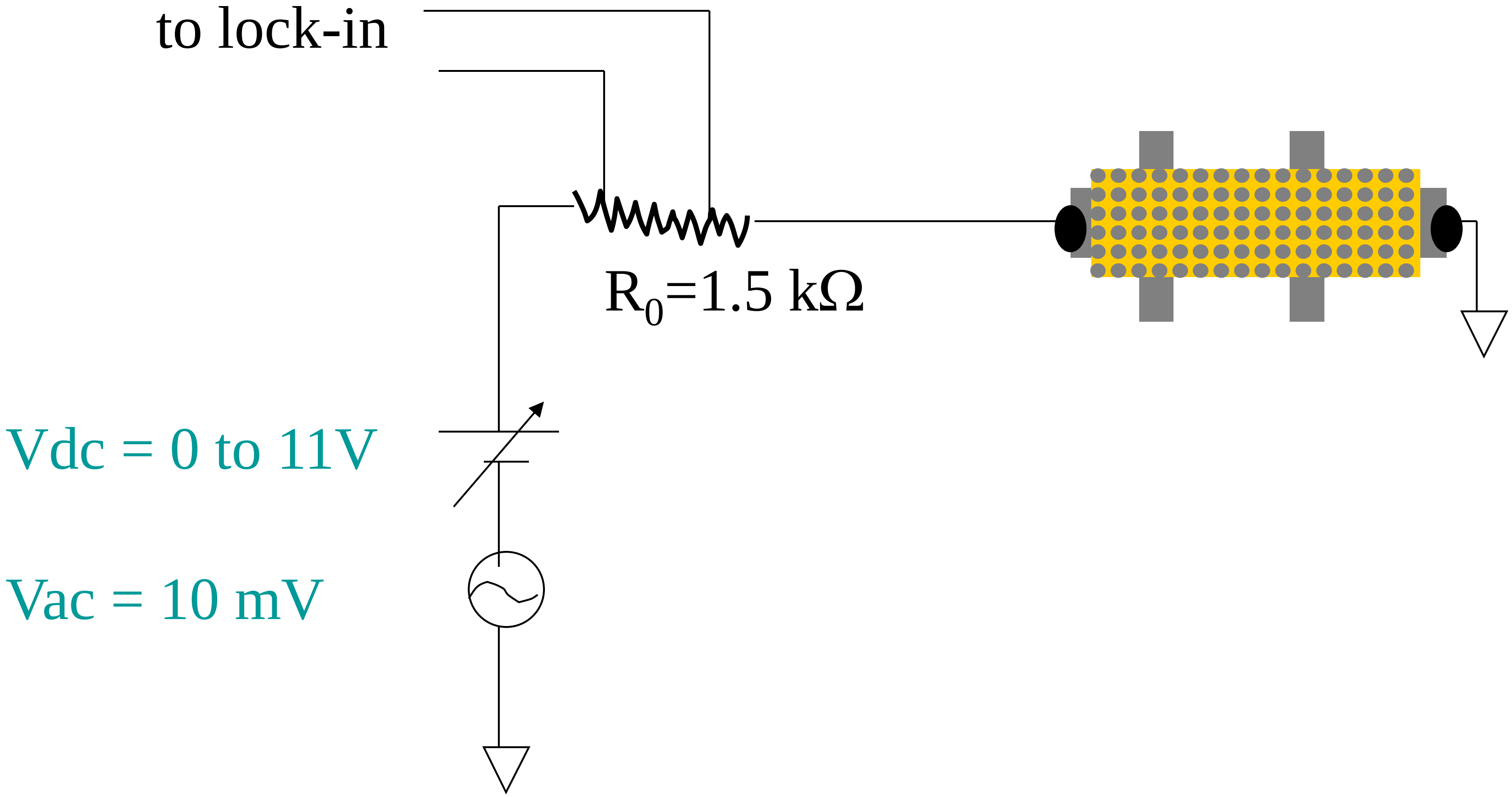
- Bloch oscillations?
- thermal runaway?
- ….

thermal runaway



Temperature dependent conductance can give rise to an apparent NDC

(Suggested by Mark Lee)

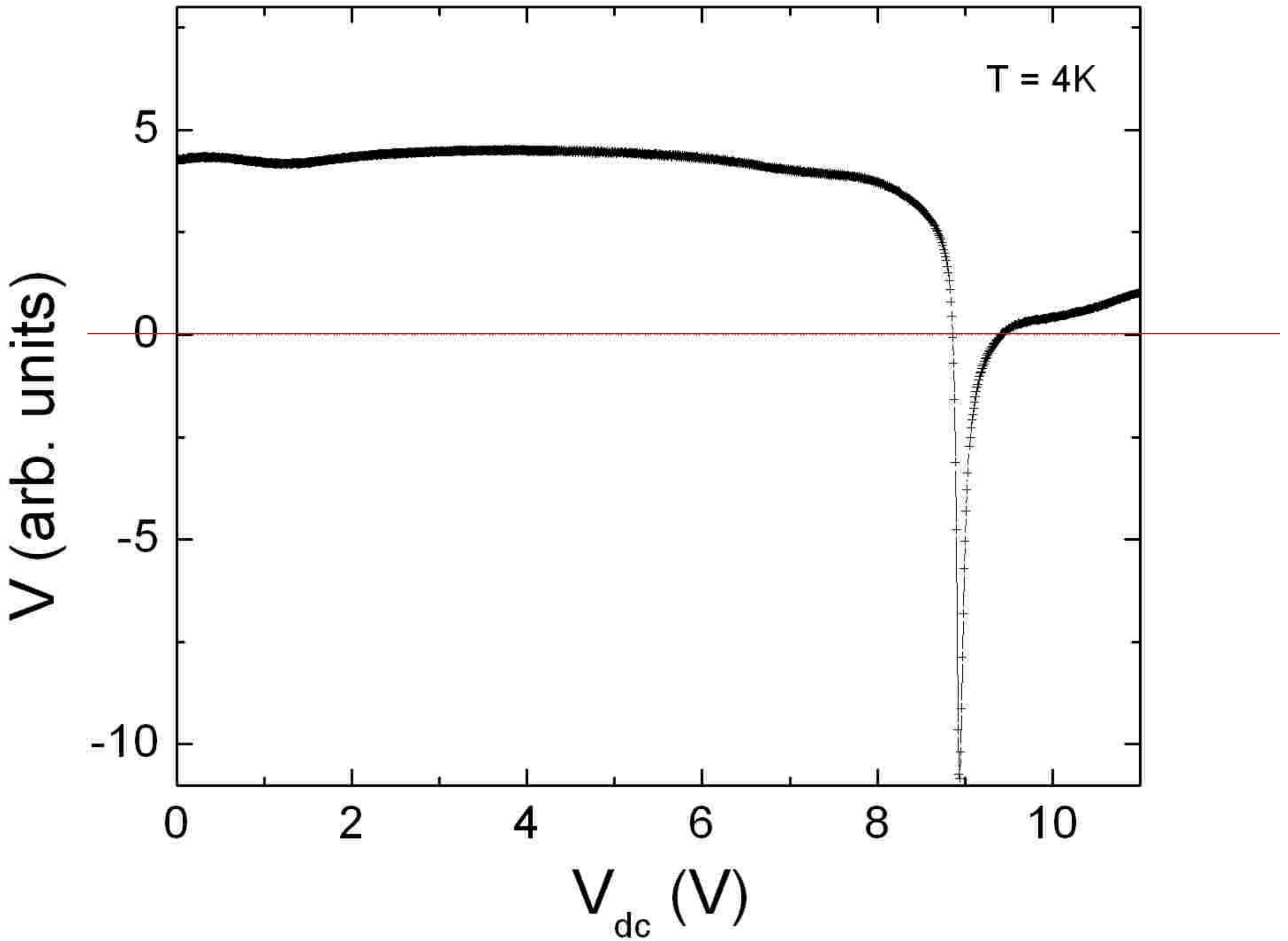


$V_{lock\text{-}in} = R_0/(R_0+r) \times Vac$

r = dV/dI, the differential resistance of Bloch sample

- **thermal runaway, r positive, $V_{lock\text{-}in} > 0$**
- **Bloch oscillations, r negative, and $|r| > R_0$, $V_{lock\text{-}in}$ is negative**

true negative differential conductance

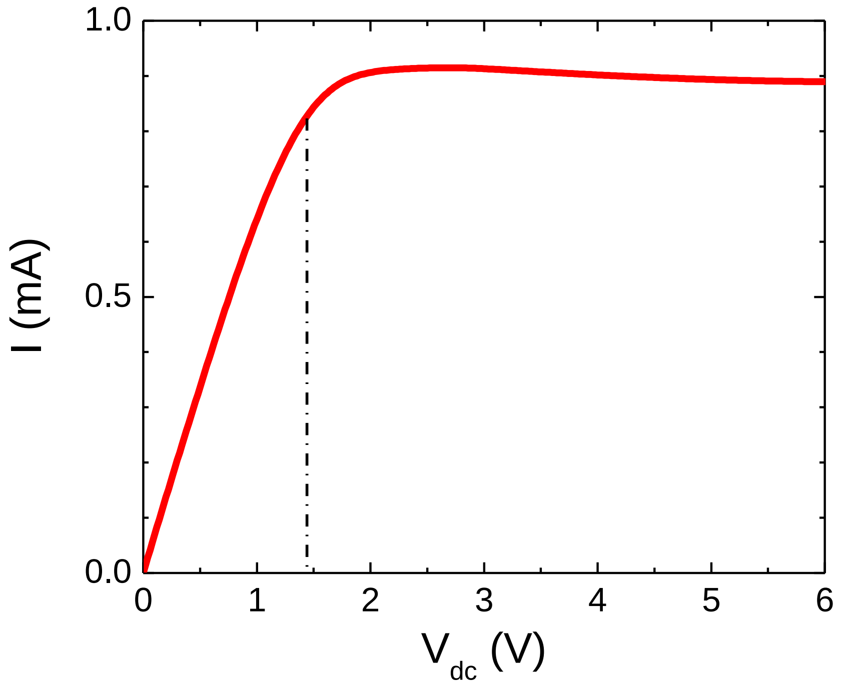


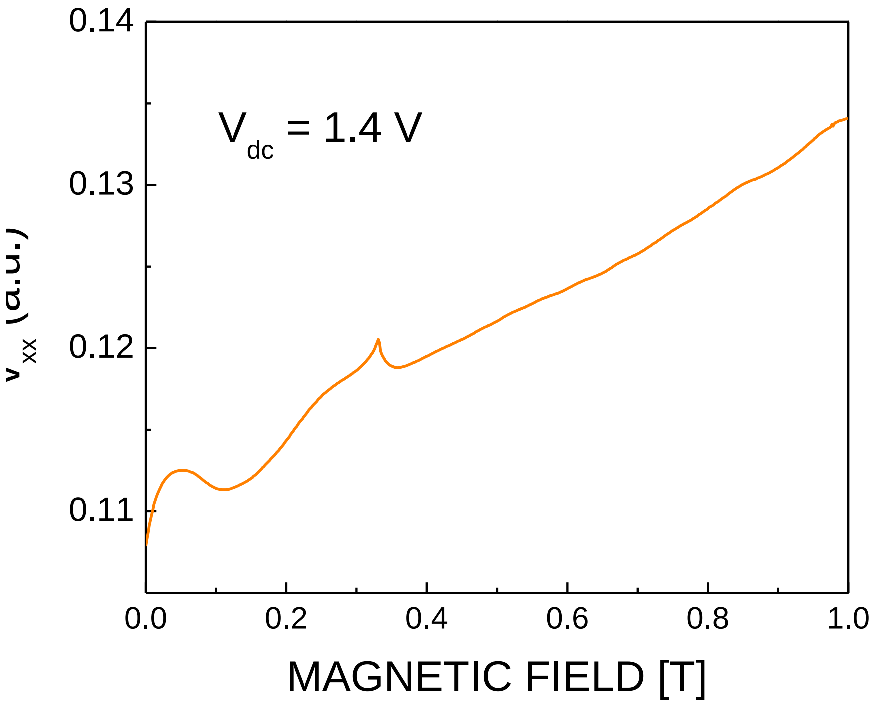
physical origin of NDC ?

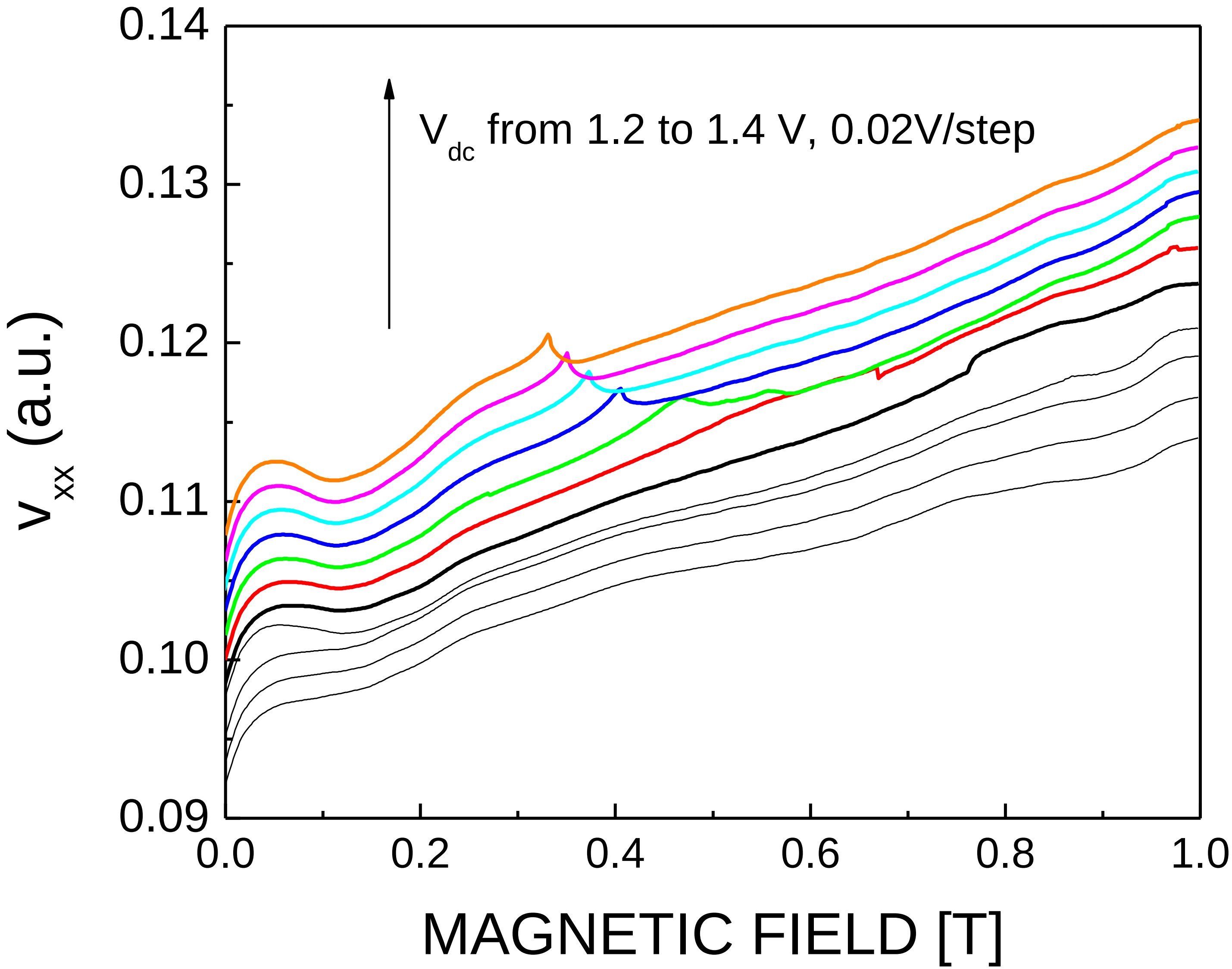
- Bloch oscillation?
- ~~thermal runaway?~~
- ….

more results on Bloch oscillations

magneto transport at high electric fields

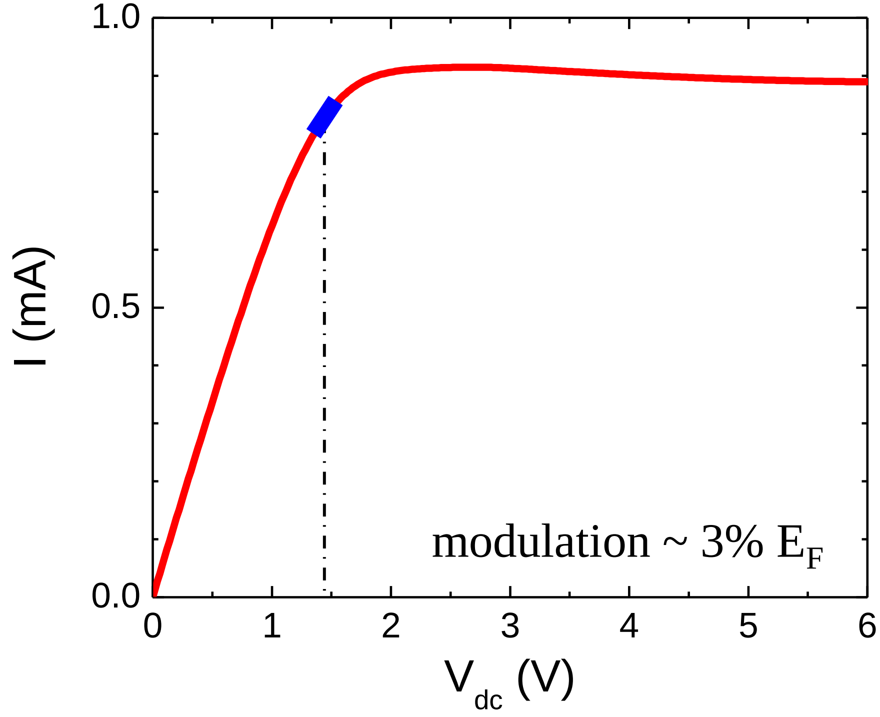


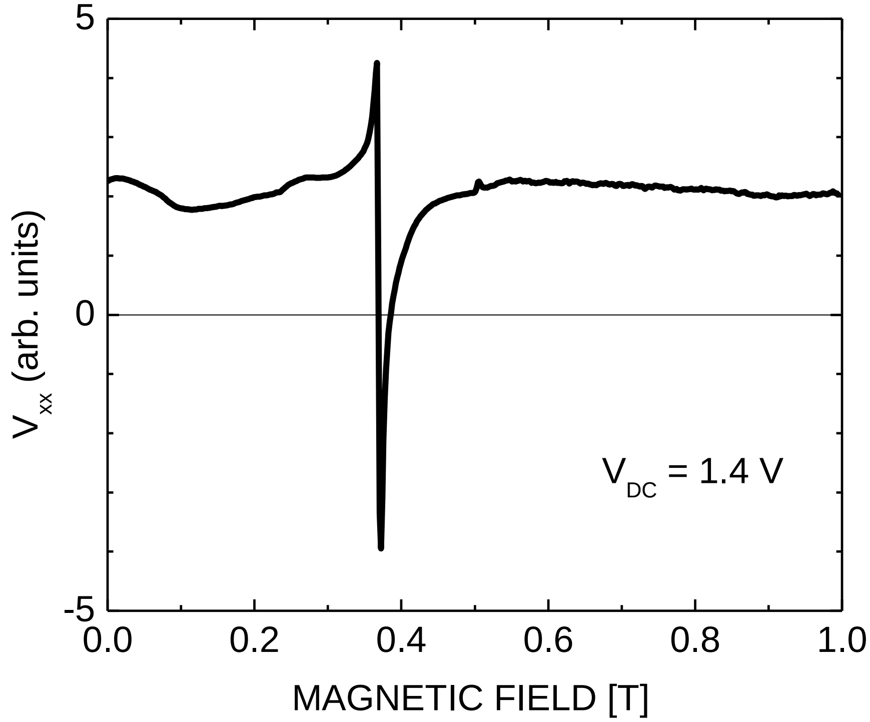


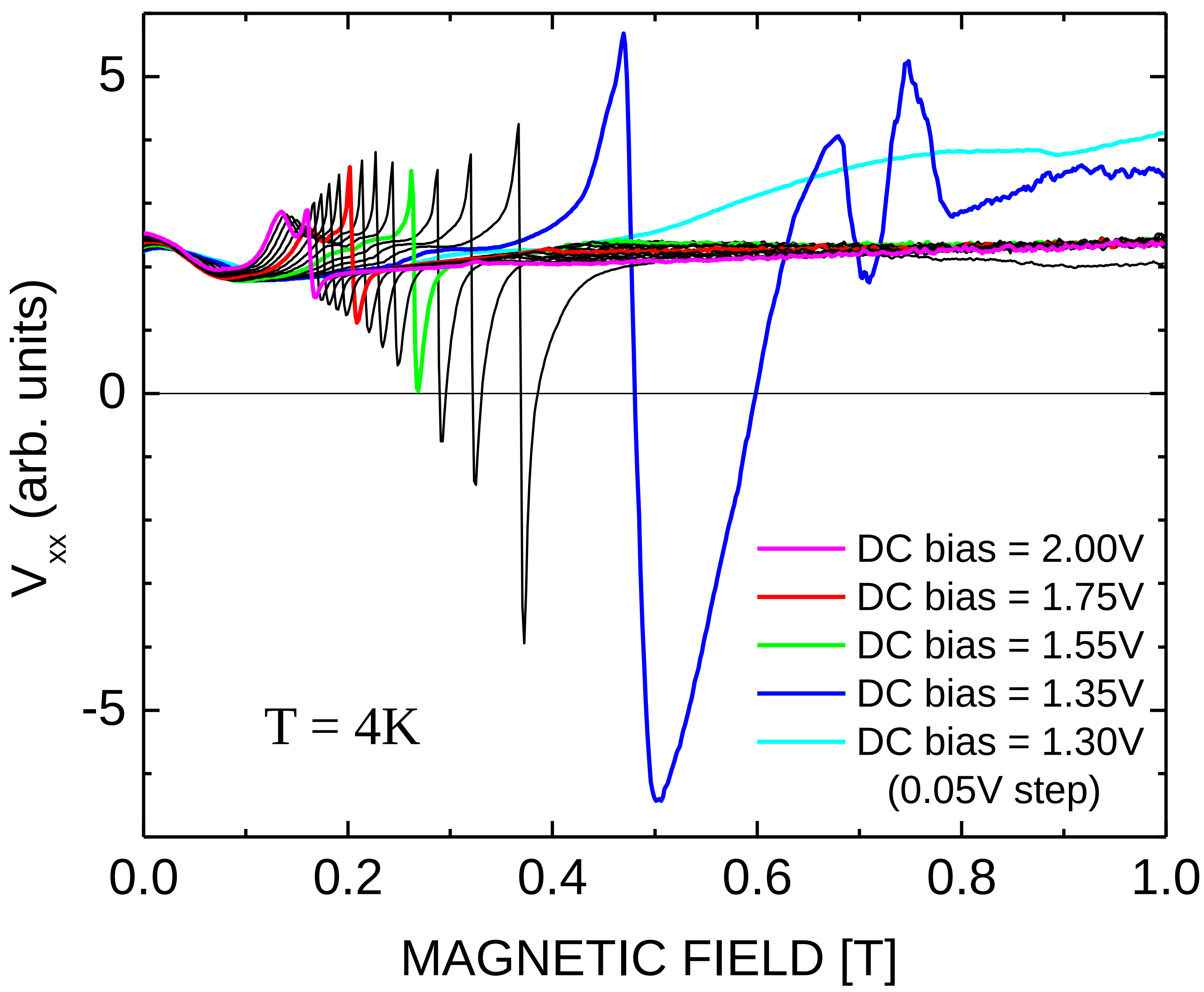


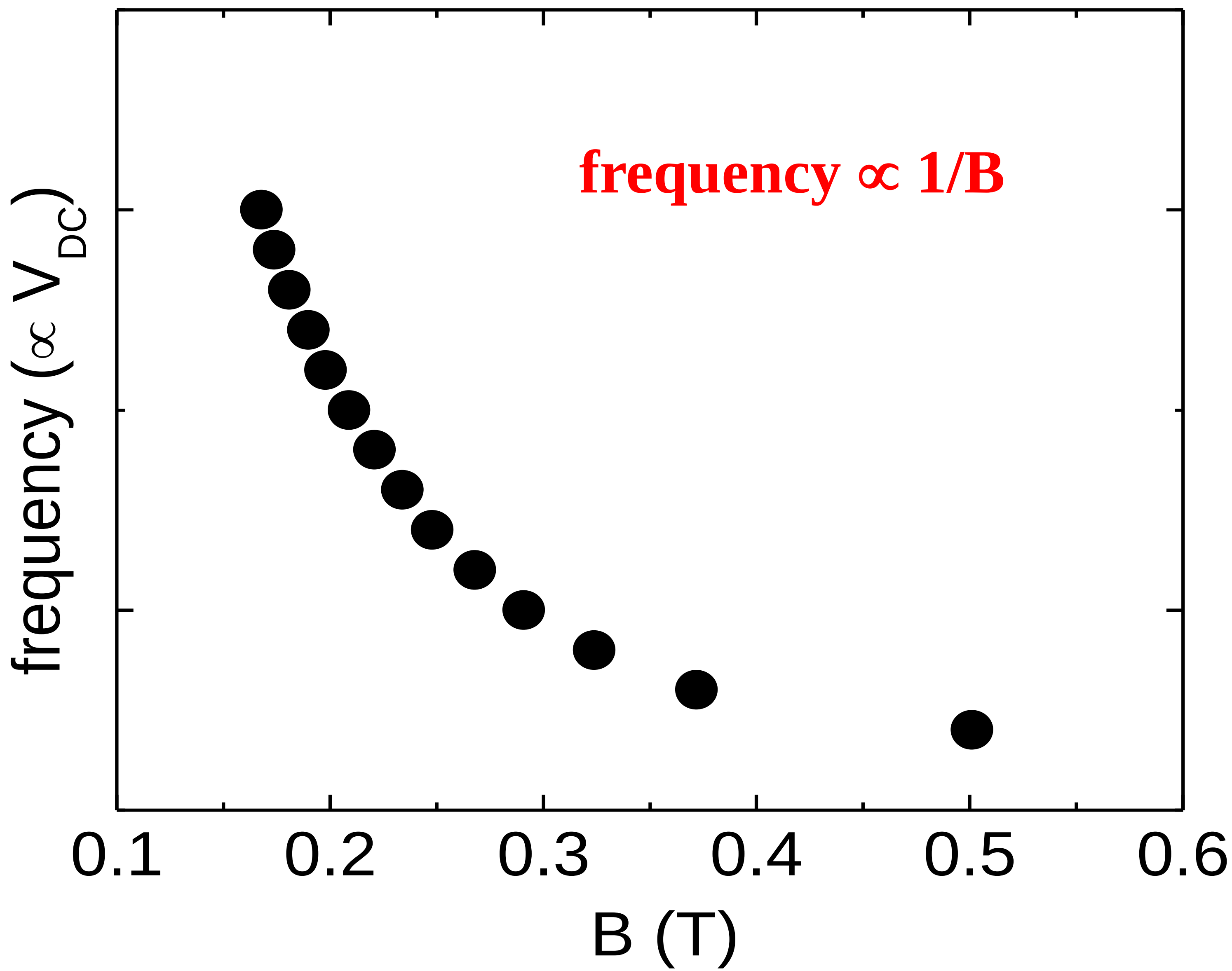
0.14
0.13
0.12
0.11
0.10
0.09
v_{xx} (a.u.)
V_{dc} from 1.2 to 1.4 V, 0.02V/step
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]

derivative measurement





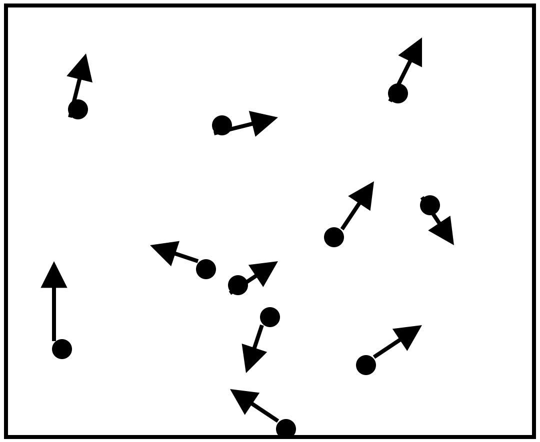

5
0
-5
V_{xx} (arb. units)
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]
T = 4K
DC bias = 2.00V
DC bias = 1.75V
DC bias = 1.55V
DC bias = 1.35V
DC bias = 1.30V
(0.05V step)



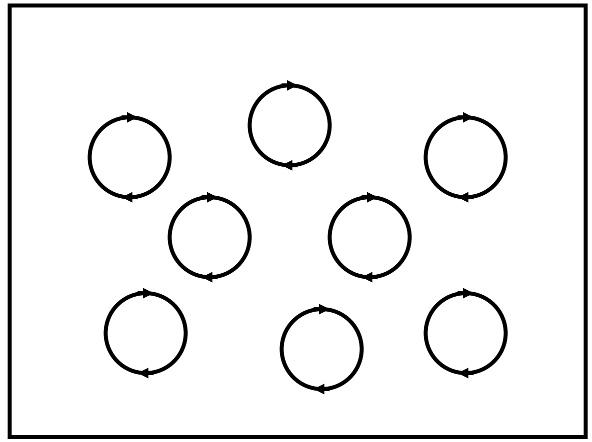
frequency ∝ 1/B
frequency (∝ V_DC)
0.1
0.2
0.3
0.4
0.5
0.6
B (T)

Cyclotron motion

$B = 0$

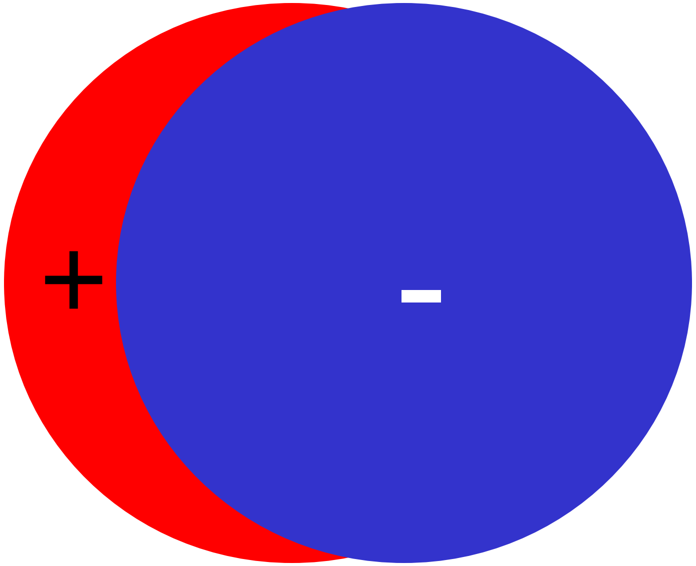


$B \neq 0$



$$\omega_c = eB/m^*$$

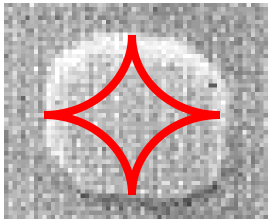
Plasmon oscillations



$$\omega_0^2 = \frac{n_s e^2 \pi}{a m^* 2(\epsilon_0 + \epsilon_1)}$$

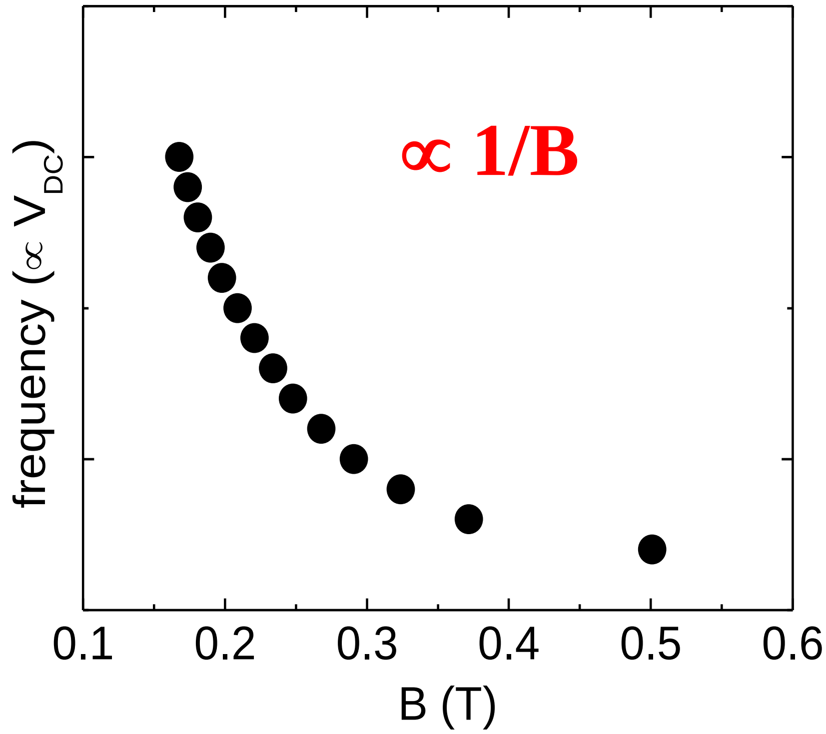
in an infinitely large sample, ω_0 is very small, no coupling between the cyclotron mode and plasmon mode.

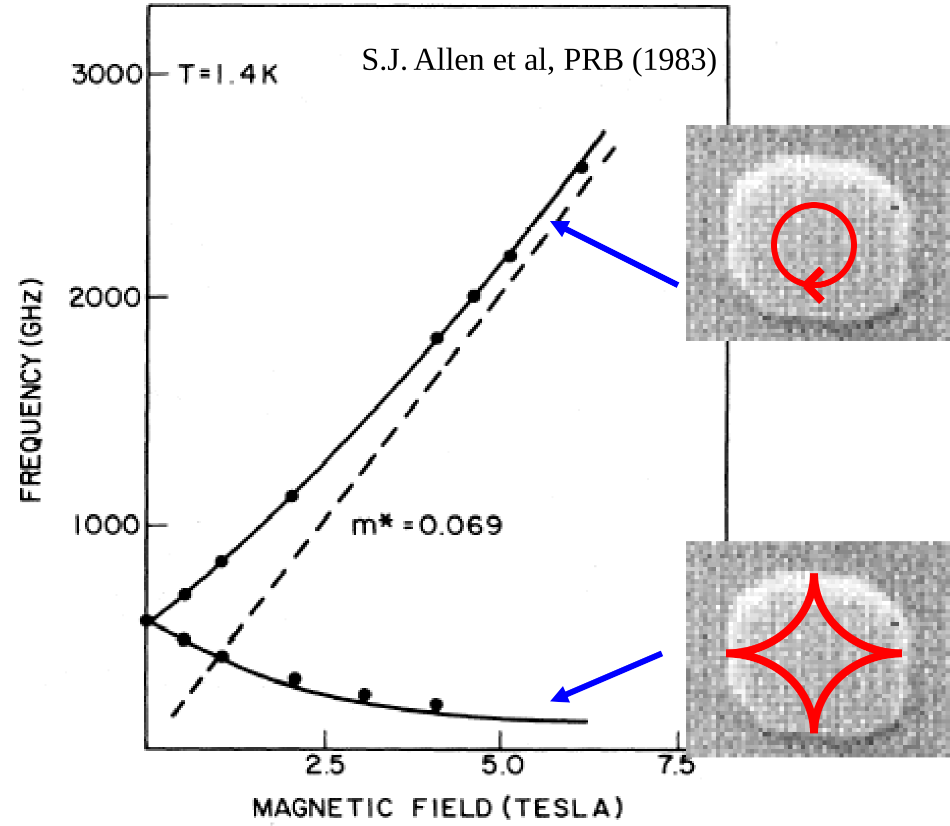
In a sample of finite size, ~ μm, there is strong coupling between the two. This results in a new resonance mode, edge magnetoplasmon mode.



$$\omega = -\omega_c/2 + [(\omega_c/2)^2 + \omega_0^2]^{1/2} \propto \mathbf{1/B} \text{ at high B fields}$$

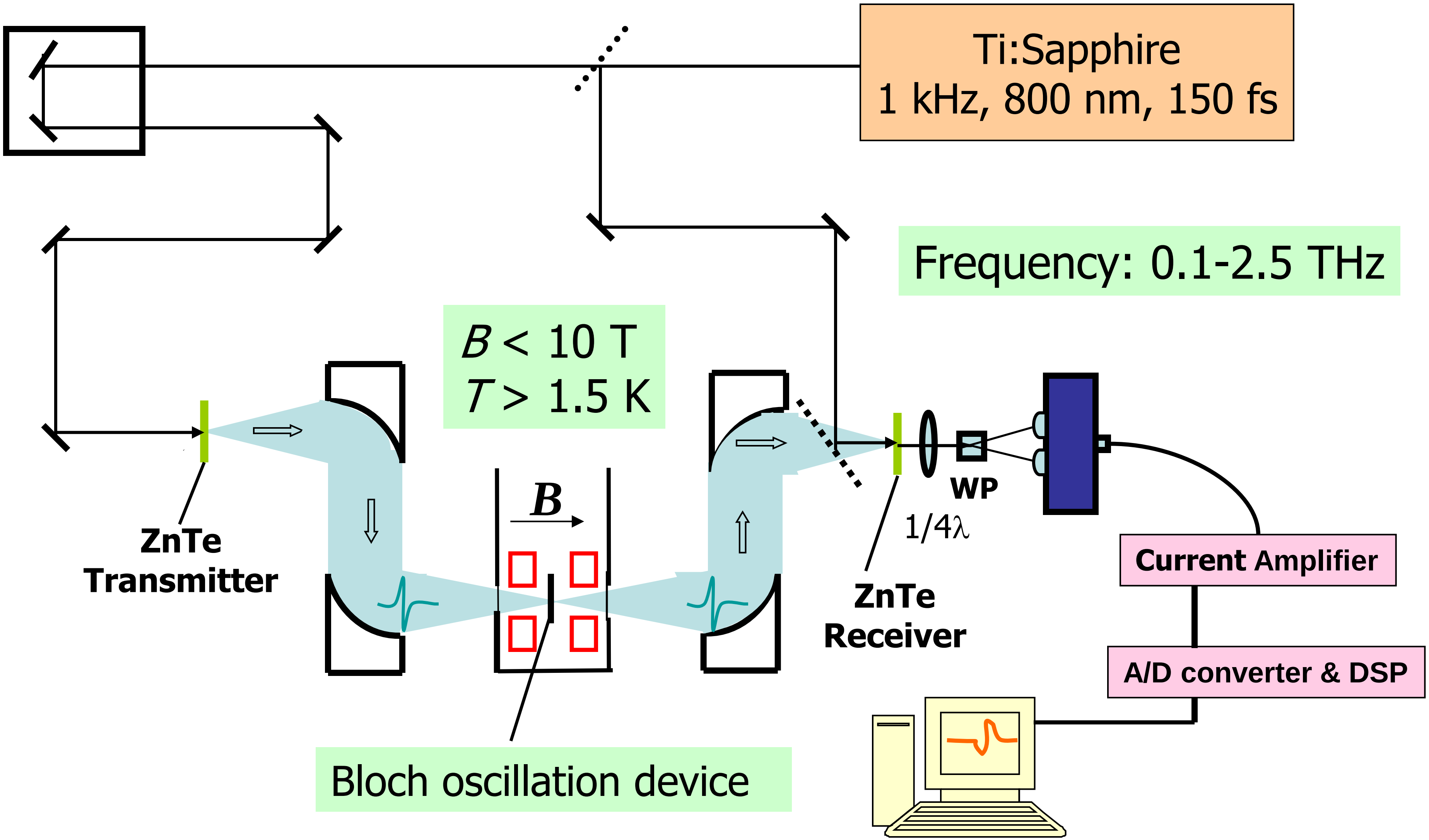
edge magnetoplasmon resonance





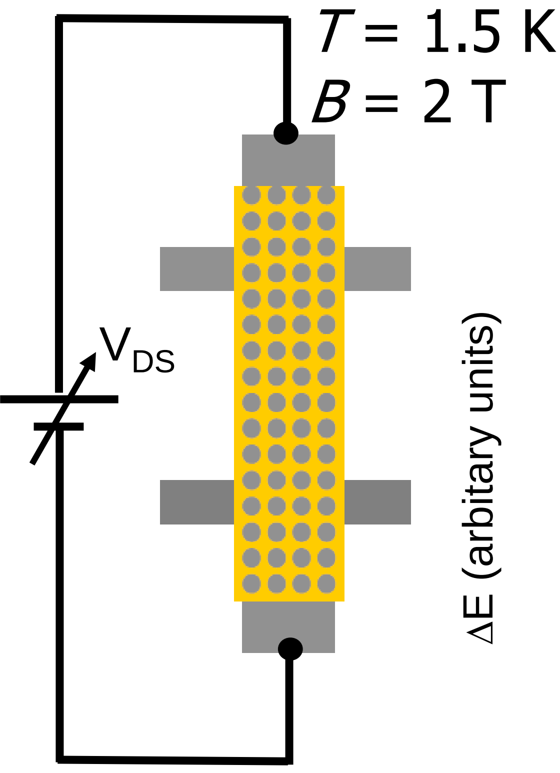
$\omega = -\omega_c/2 + [(\omega_c/2)^2 + \omega_0{}^2]^{1/2} \propto$ **1/B** at high B fields

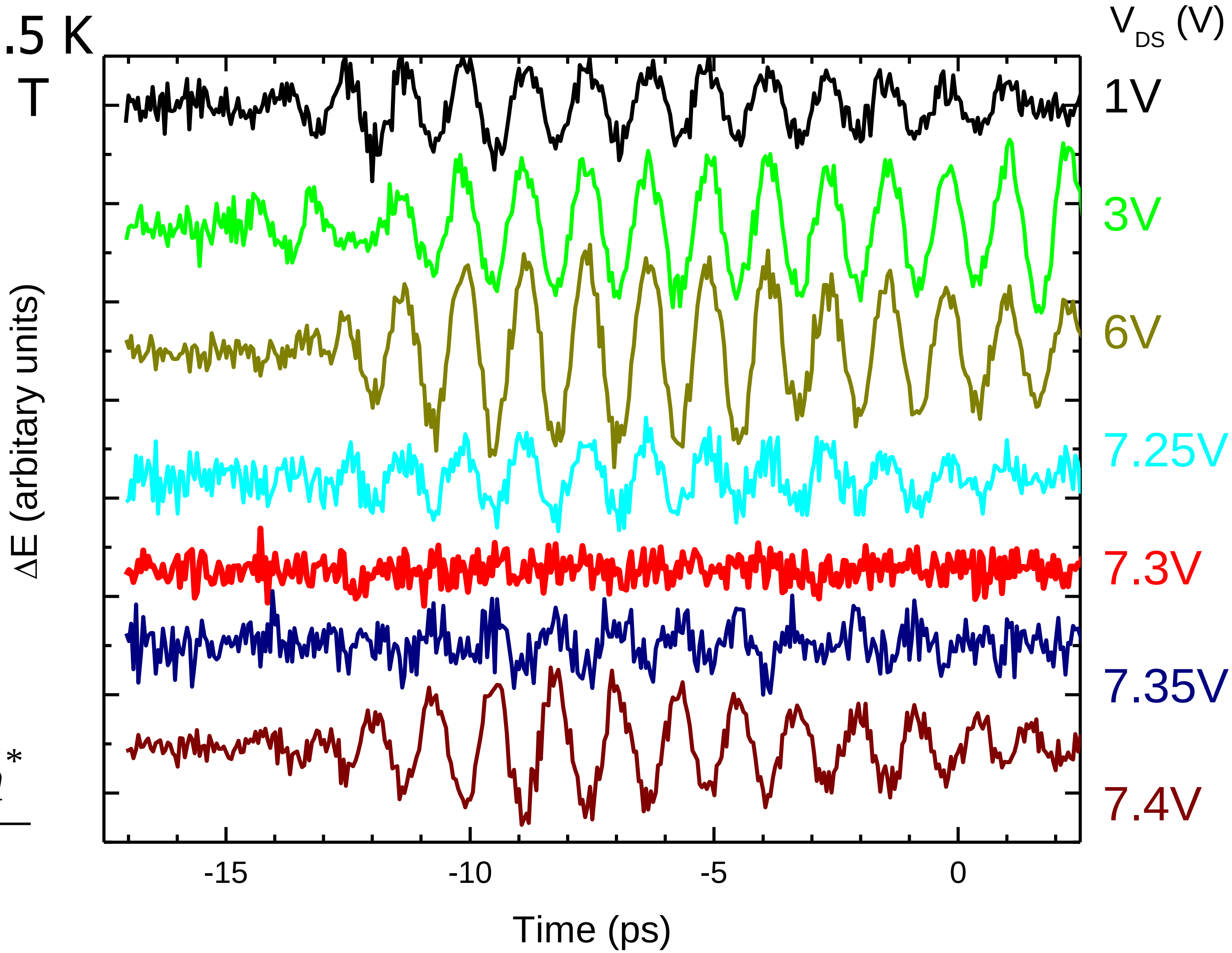
time-domain THz magneto-spectroscopy



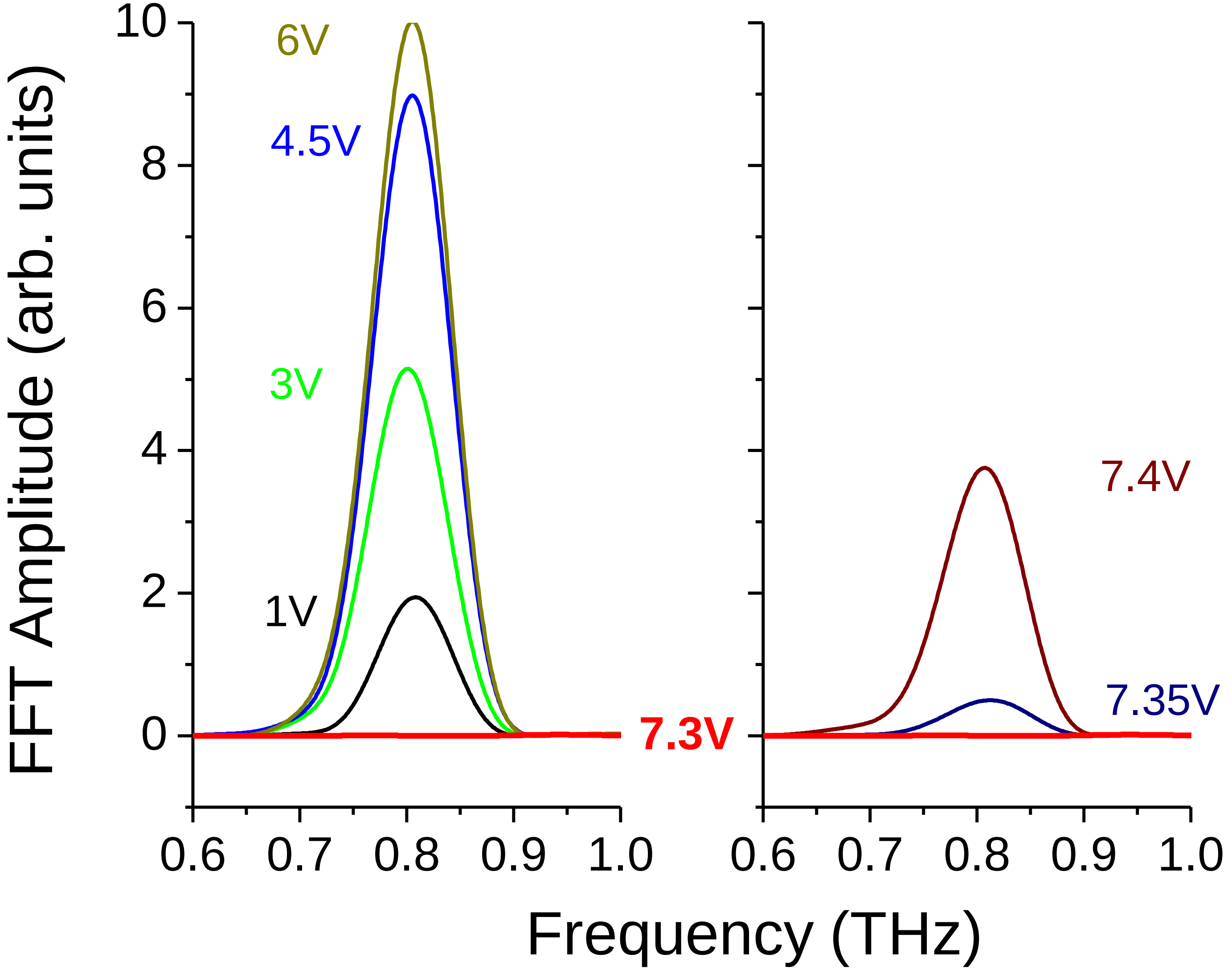
in collaboration with Jun Kono at Rice Univ.

coherent cyclotron resonance in Bloch oscillator



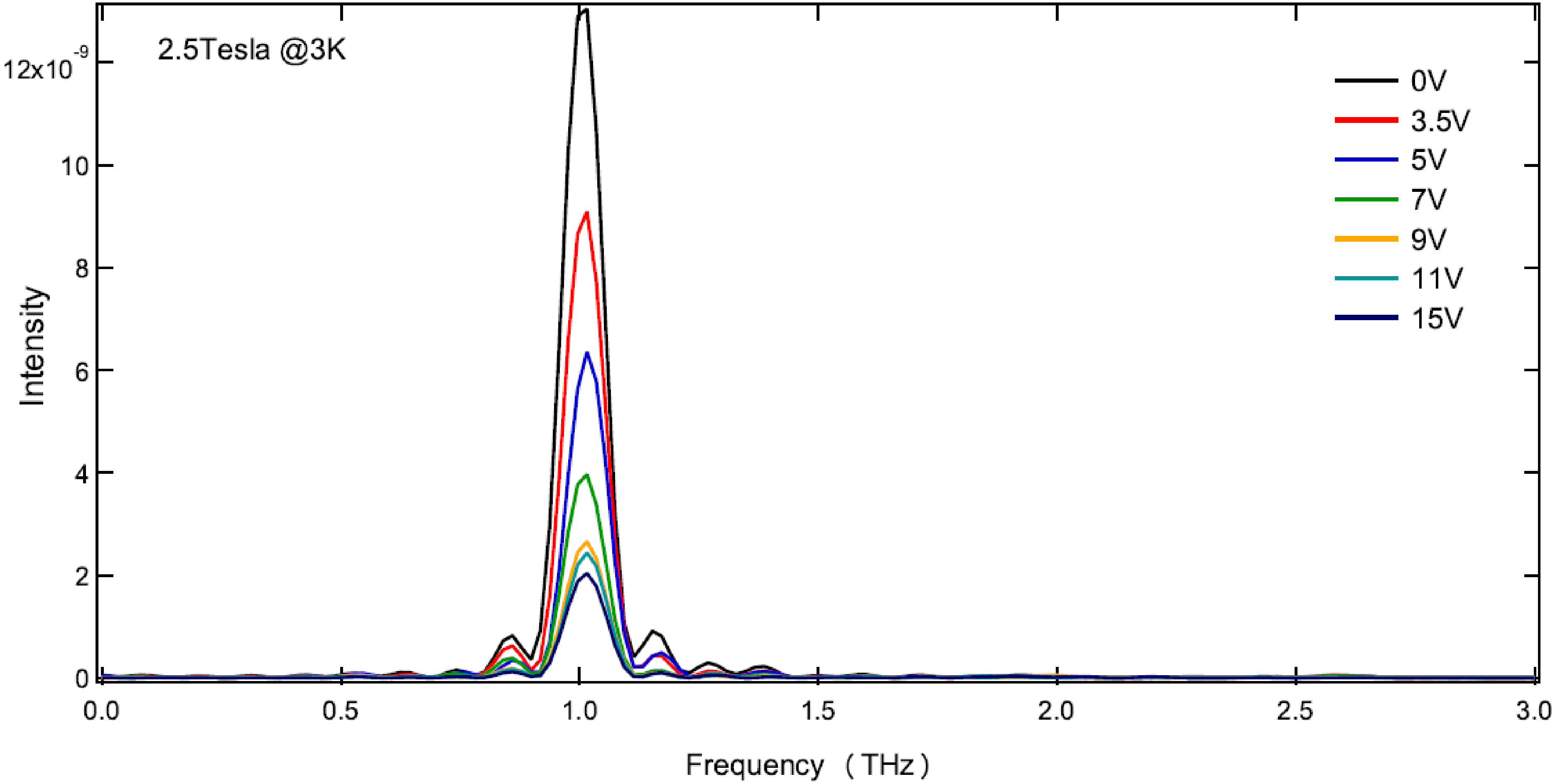


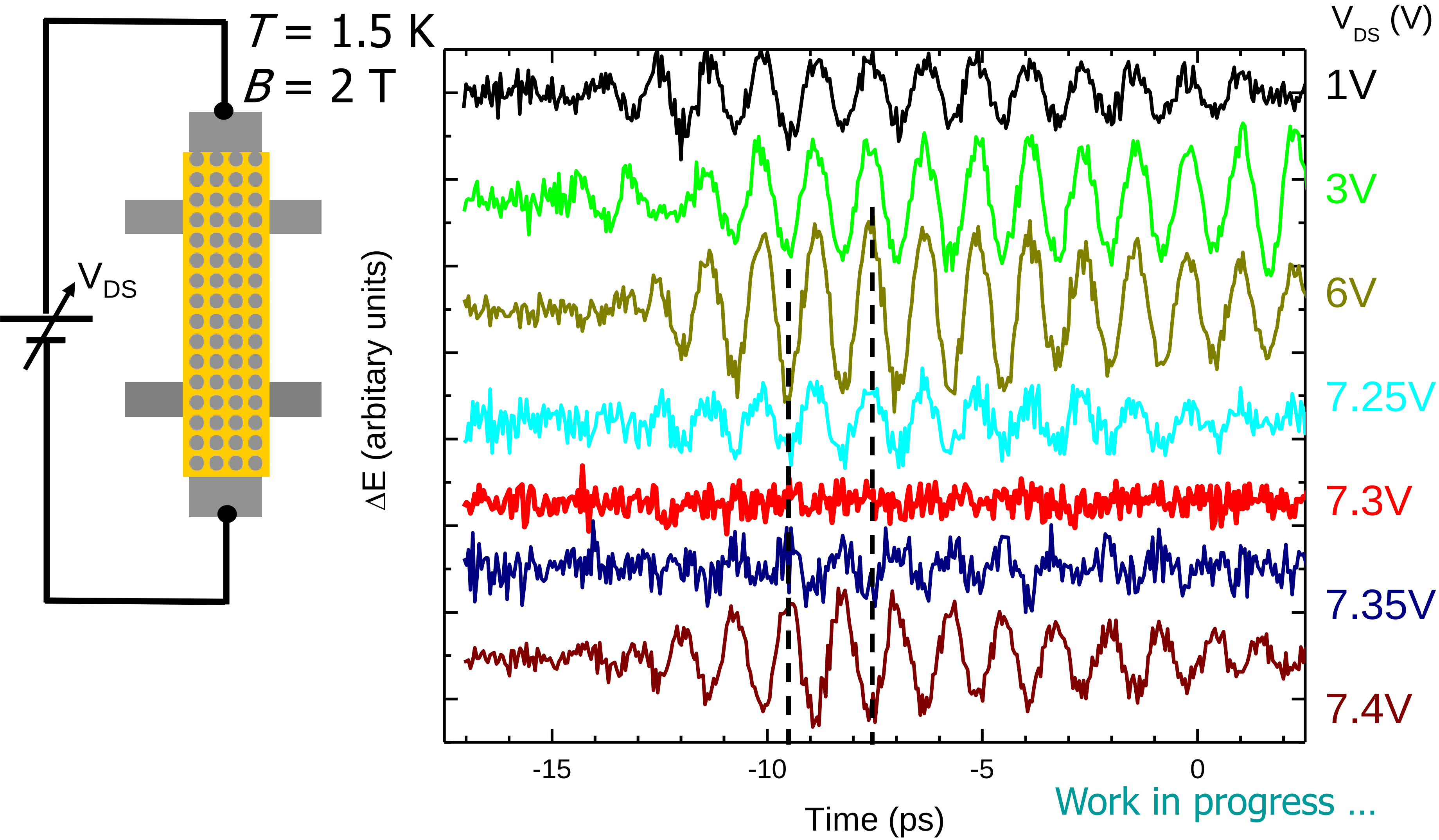
$$T_c = \frac{2\pi}{\omega_c} = \frac{2\pi m^*}{eB}$$



FFT Amplitude (arb. units)
10
8
6
4
2
0
6V
4.5V
3V
1V
7.3V
7.4V
7.35V
0.6
0.7
0.8
0.9
1.0
0.6
0.7
0.8
0.9
1.0
Frequency (THz)

2D sample without patterning





E-Field-Induced THz Phase Flip!

collaborators

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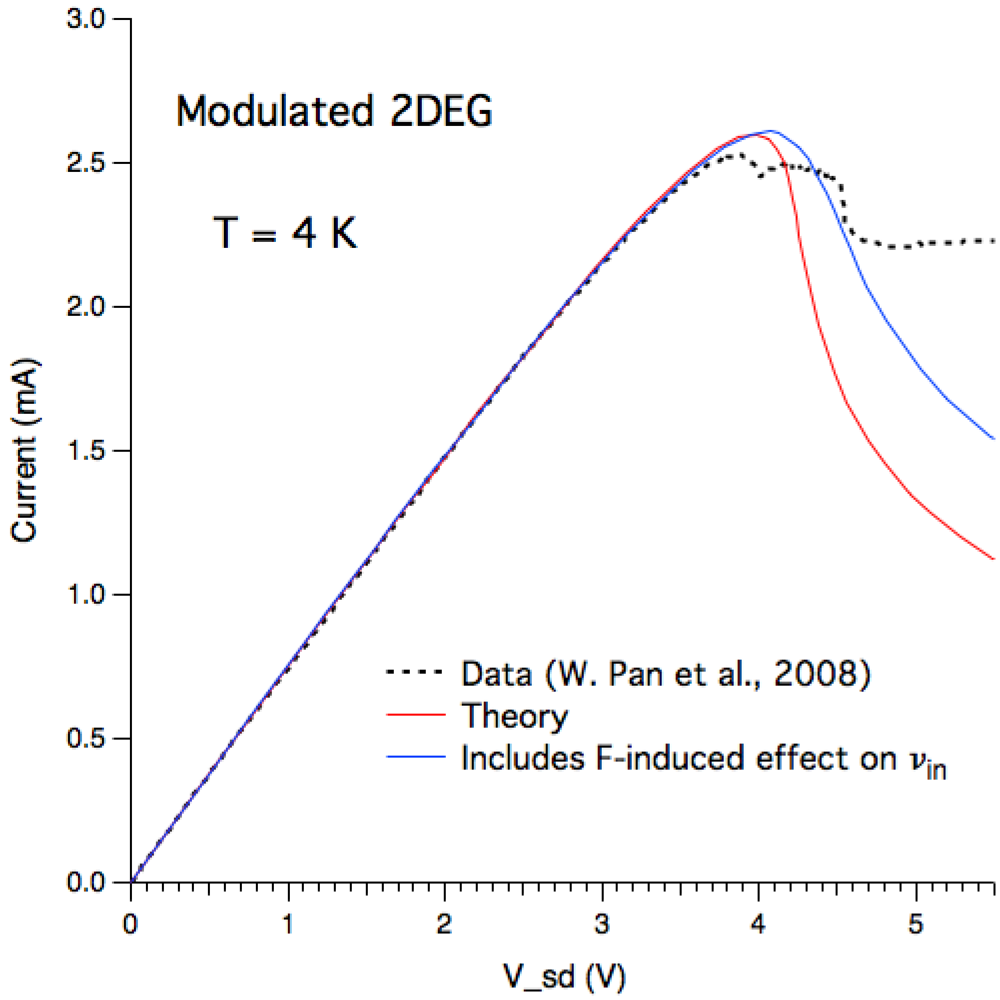
J. Kono
Rice University

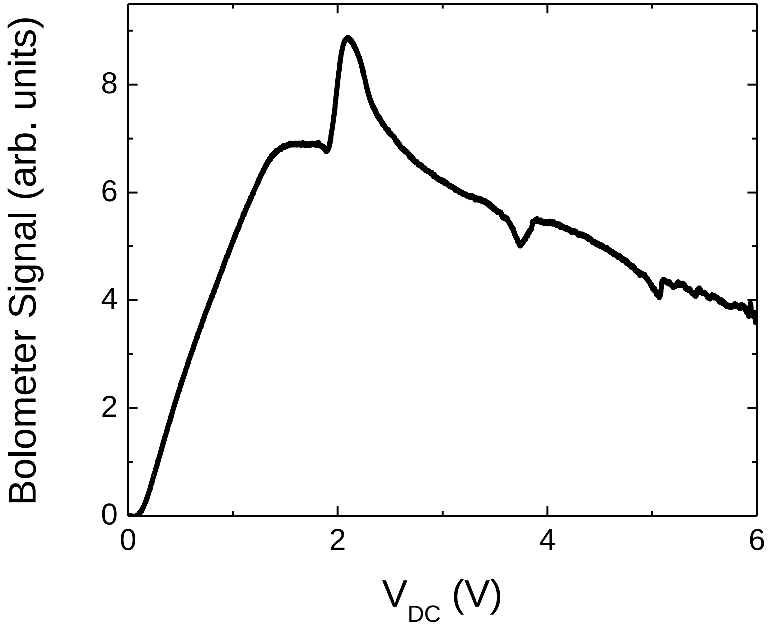
Thank you!

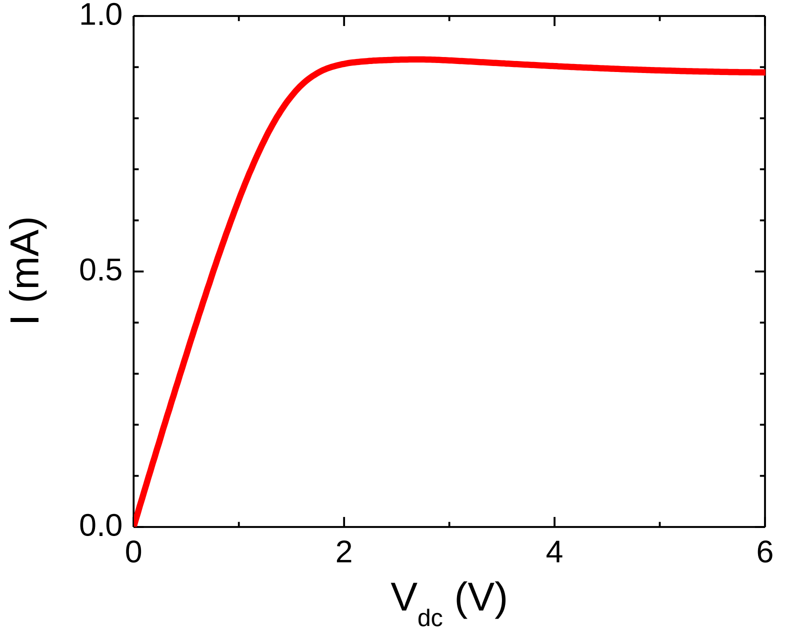
theoretical work on Bloch oscillations

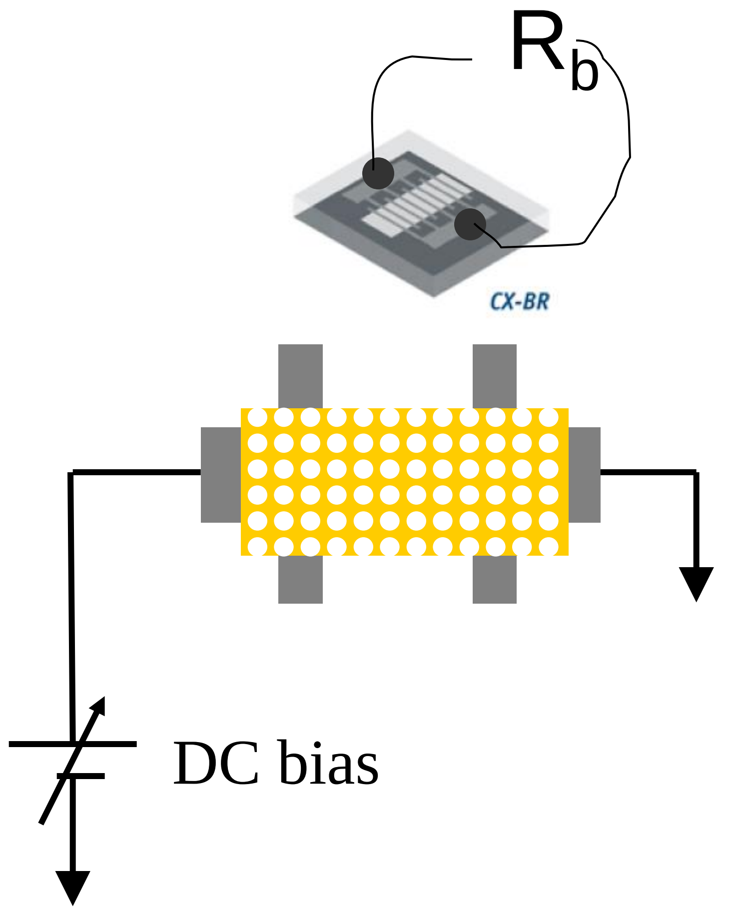
Ken Lyo



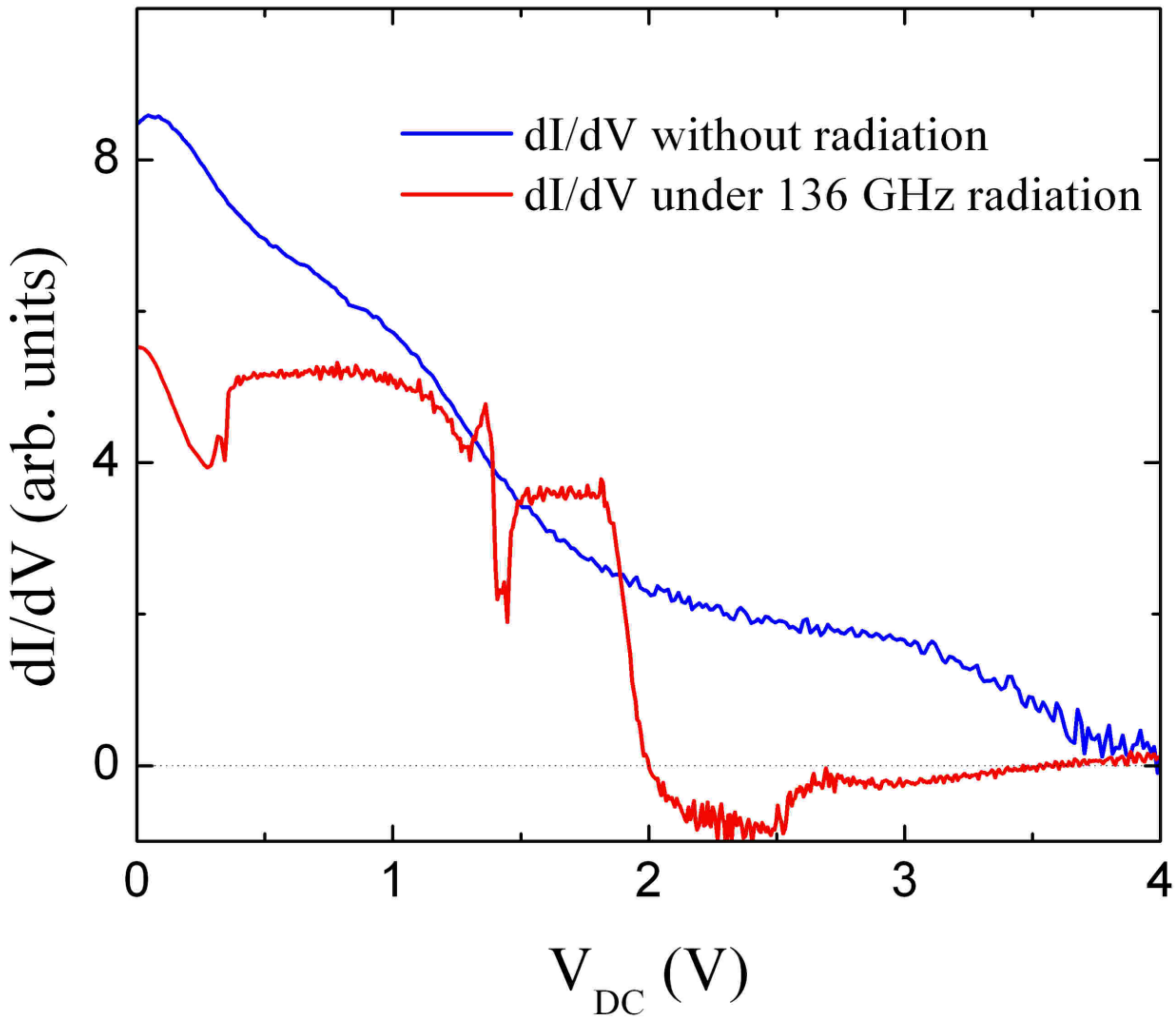
bolometric measurements





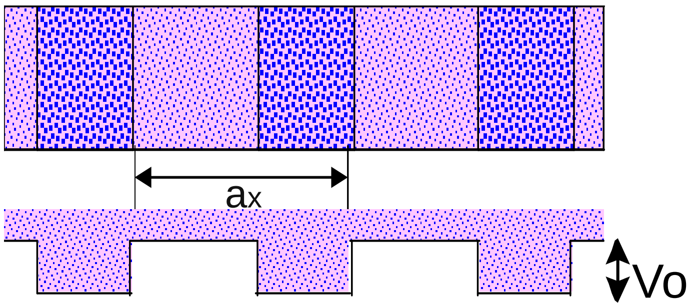


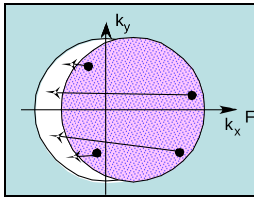
inversed BO measurements



Theoretical model: 1D Modulation

Modulated 2DEG





Inelastic scattering rate is enhanced by F-induced emission of phonons.

Exact relaxation-time solution

Inelastic relax rate

Fermi function

elastic scattering

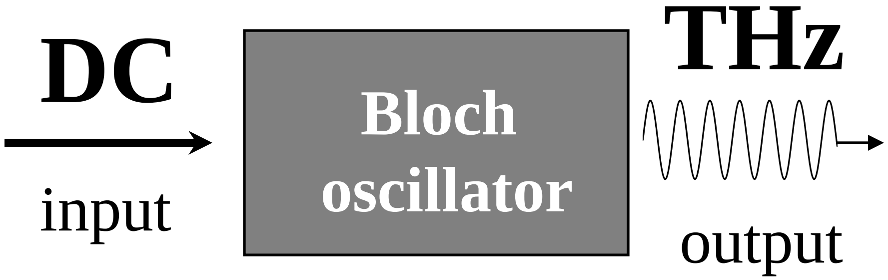
$$-\frac{eF}{\hbar}\frac{\partial f_n(\mathbf{k})}{\partial k_x} = -\nu_{in}[f_n(\mathbf{k}) - f^{(0)}(\varepsilon_{n,\mathbf{k}})] - \frac{2\pi}{\hbar}\sum_{n',\mathbf{k}'}|U|^2[f_n(\mathbf{k}) - f_{n'}(\mathbf{k}')]\delta(\varepsilon_{n,\mathbf{k}} - \varepsilon_{n',\mathbf{k}'})$$

Esaki-Tsu (1970)
1D gas

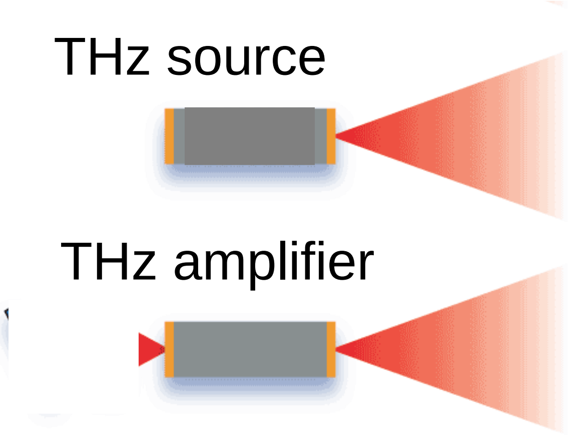
modified version of
Gerhardts (1993-3D gas)

interband scattering

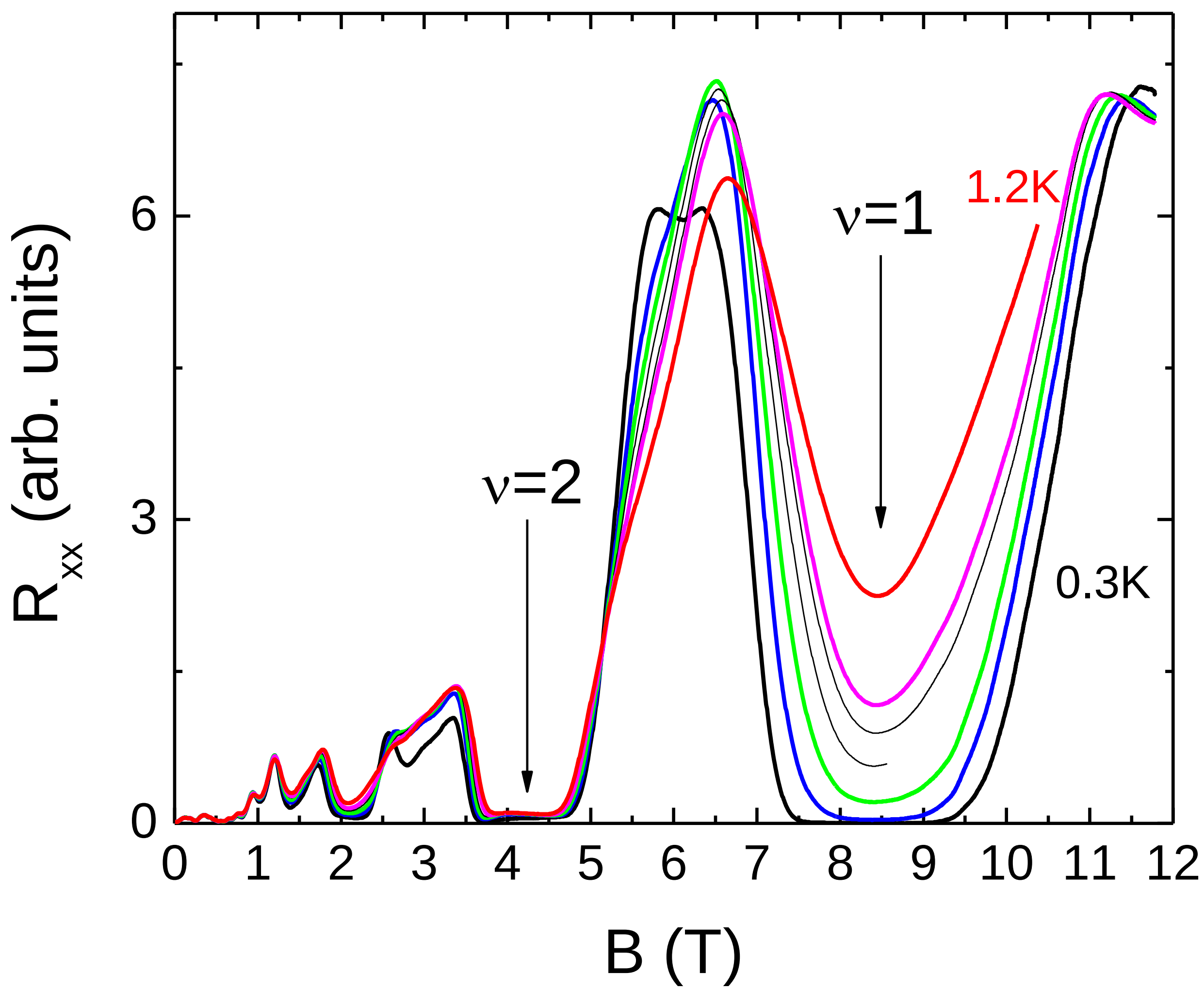
solid state, electrically biased THz emitter

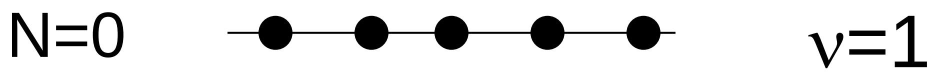


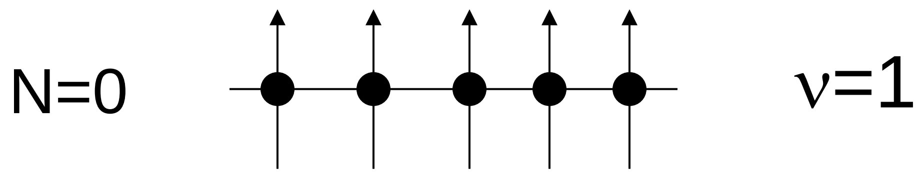
- THz emission
- THz amplification



weak ν=1 integer quantum Hall state



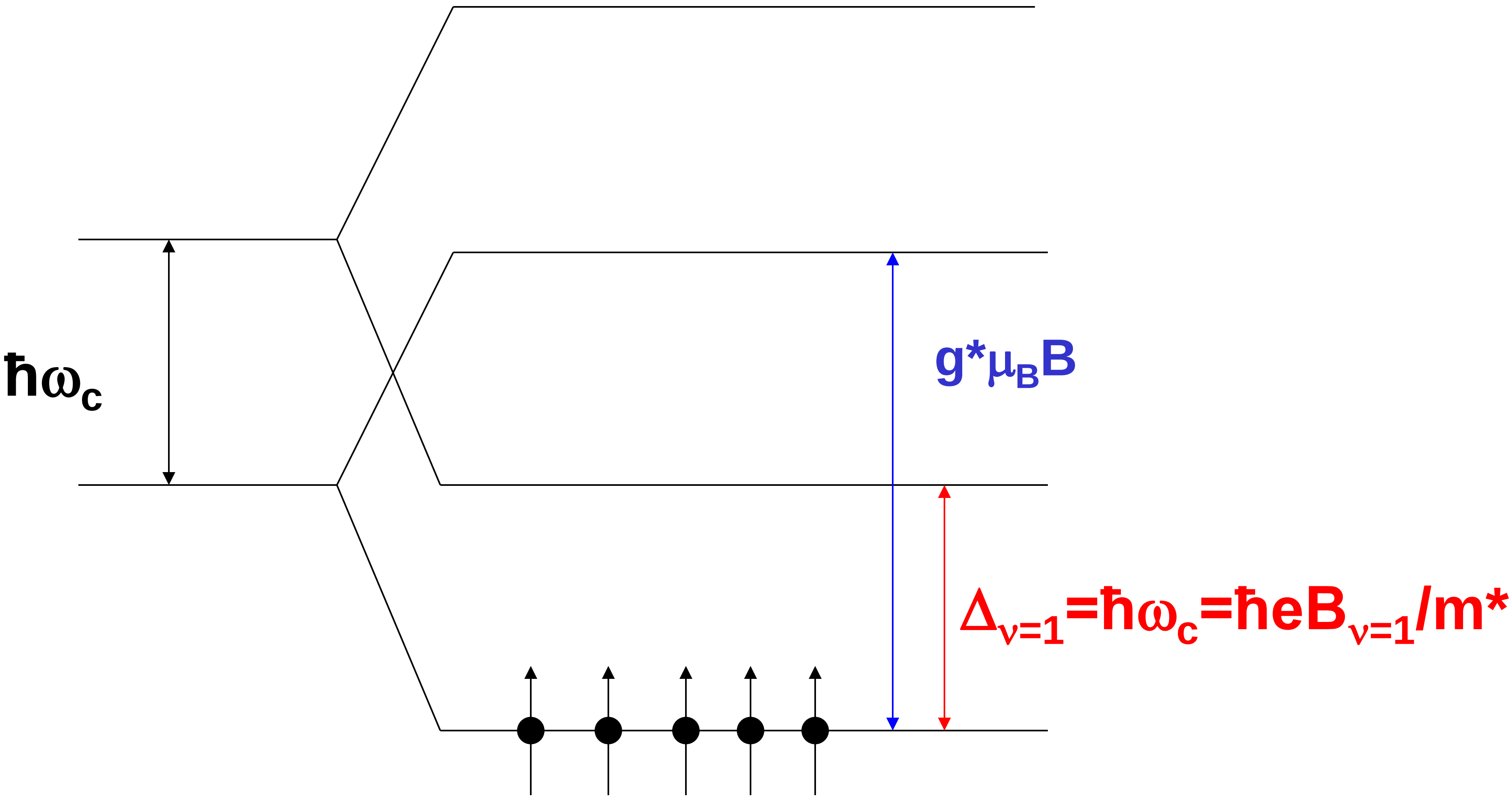


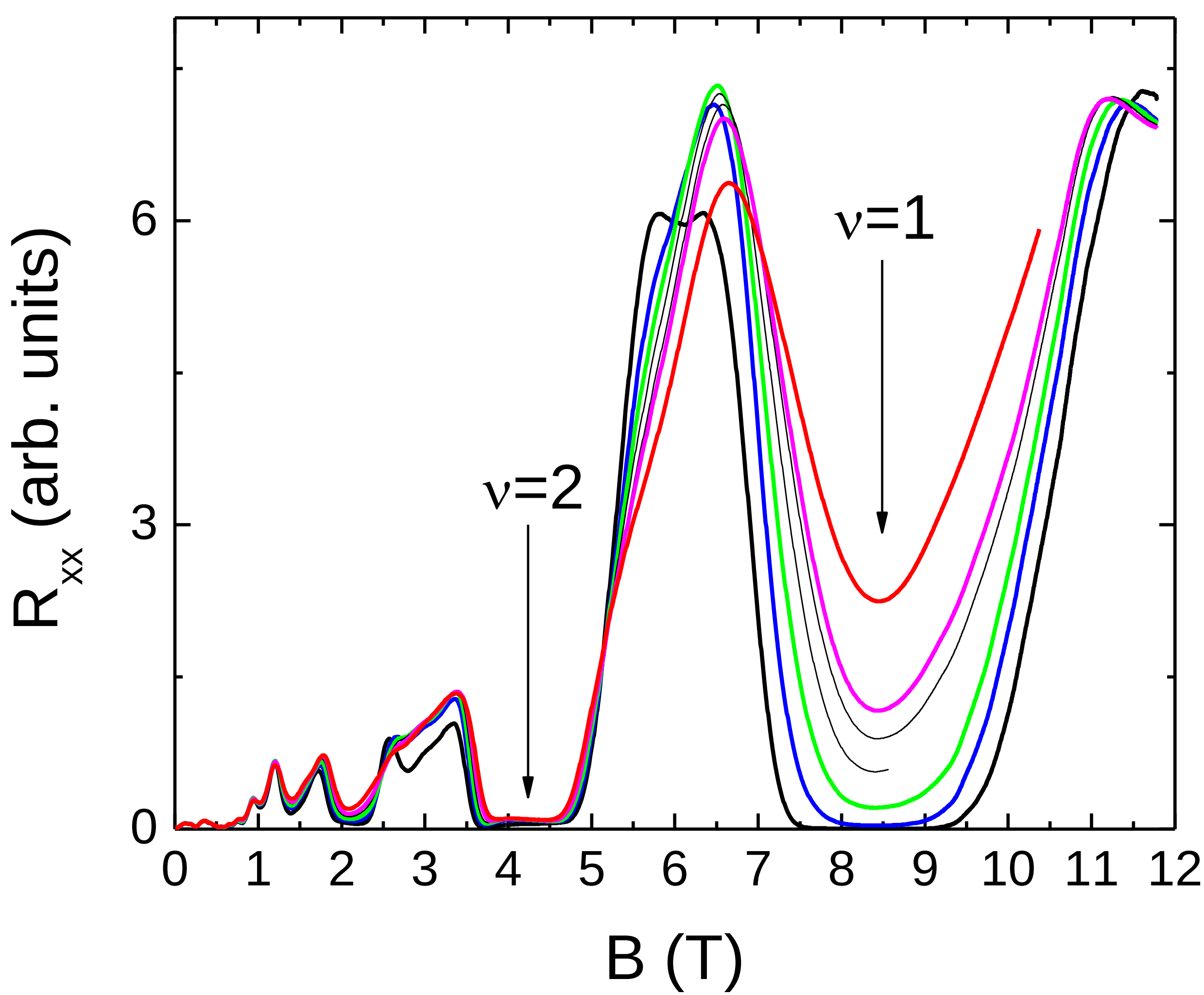


electron-electron interaction → quantum Hall ferromagnetic state

g-factor enhanced

Yarlagadda and Giuliani, Phys. Rev. B (1988)


$\hbar\omega_c$
$g^*\mu_B B$
$\Delta_{\nu=1}=\hbar\omega_c=\hbar eB_{\nu=1}/m^*$



R_{xx} (arb. units)
B (T)
ν=2
ν=1
0
3
6
0
1
2
3
4
5
6
7
8
9
10
11
12

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Disorder and interactions in quantum Hall ferromagnets near $\nu=1$

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(Received 19 April 2000)

PHYSICAL REVIEW B, VOLUME 64, 241309(R)

Effects of disorder on the $\nu=1$ quantum Hall state

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(Received 10 October 2001; published 10 December 2001)

PHYSICAL REVIEW B, VOLUME 65, 195310

Activation energy in a quantum Hall ferromagnet and non-Hartree-Fock skyrmions

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(Received 3 August 2001; revised manuscript received 17 December 2001; published 2 May 2002)

Spin Textures, Screening, and Excitations in Dirty Quantum Hall Ferromagnets

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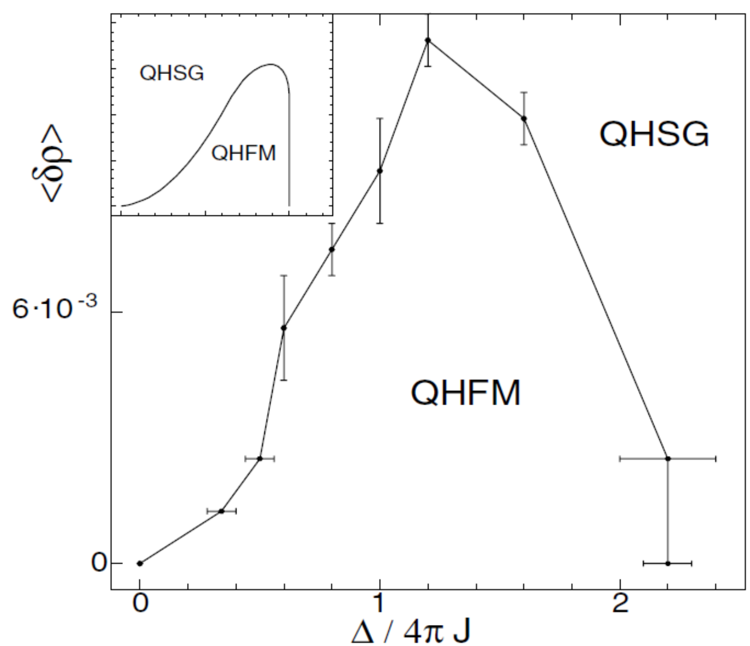
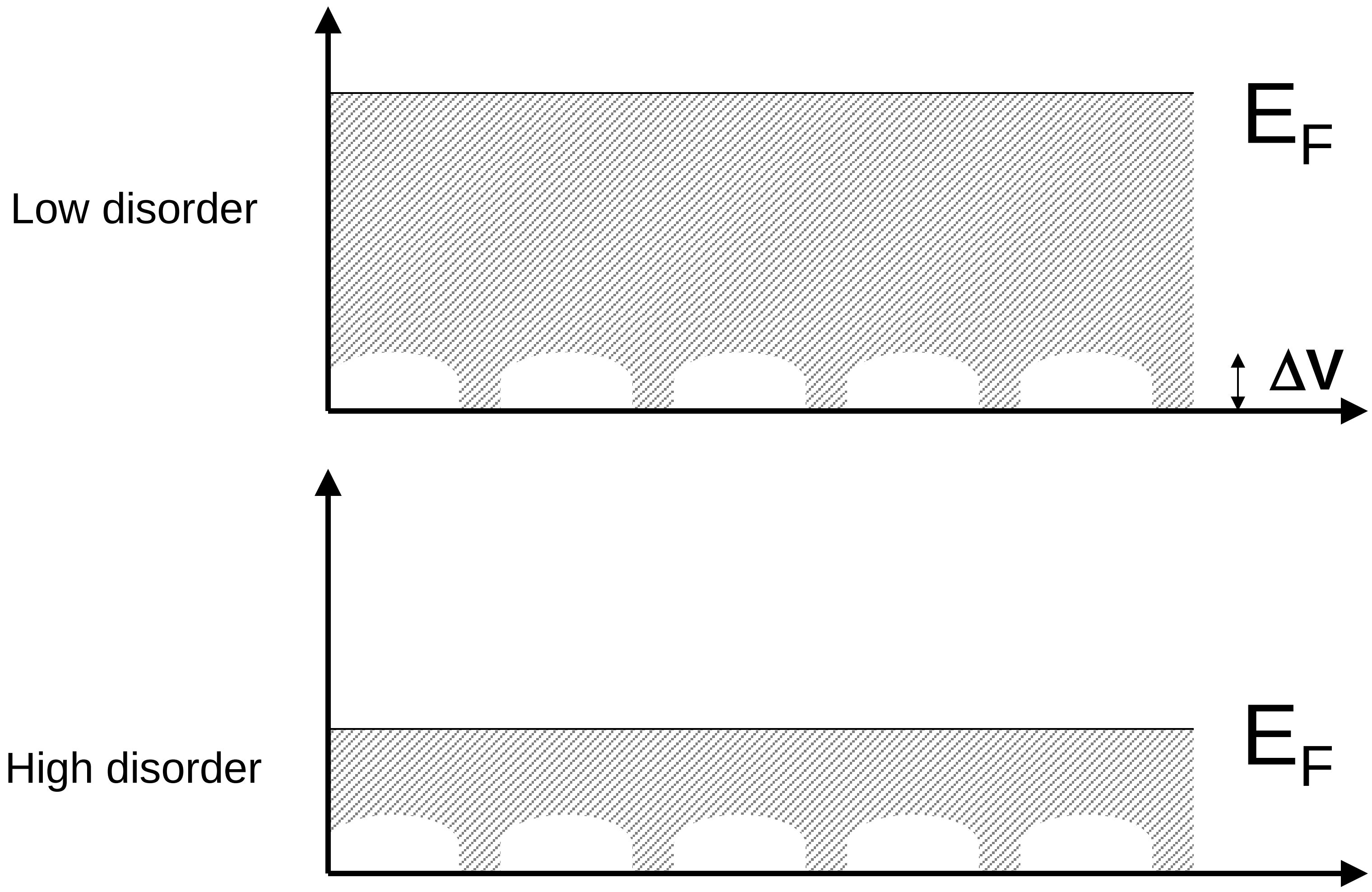
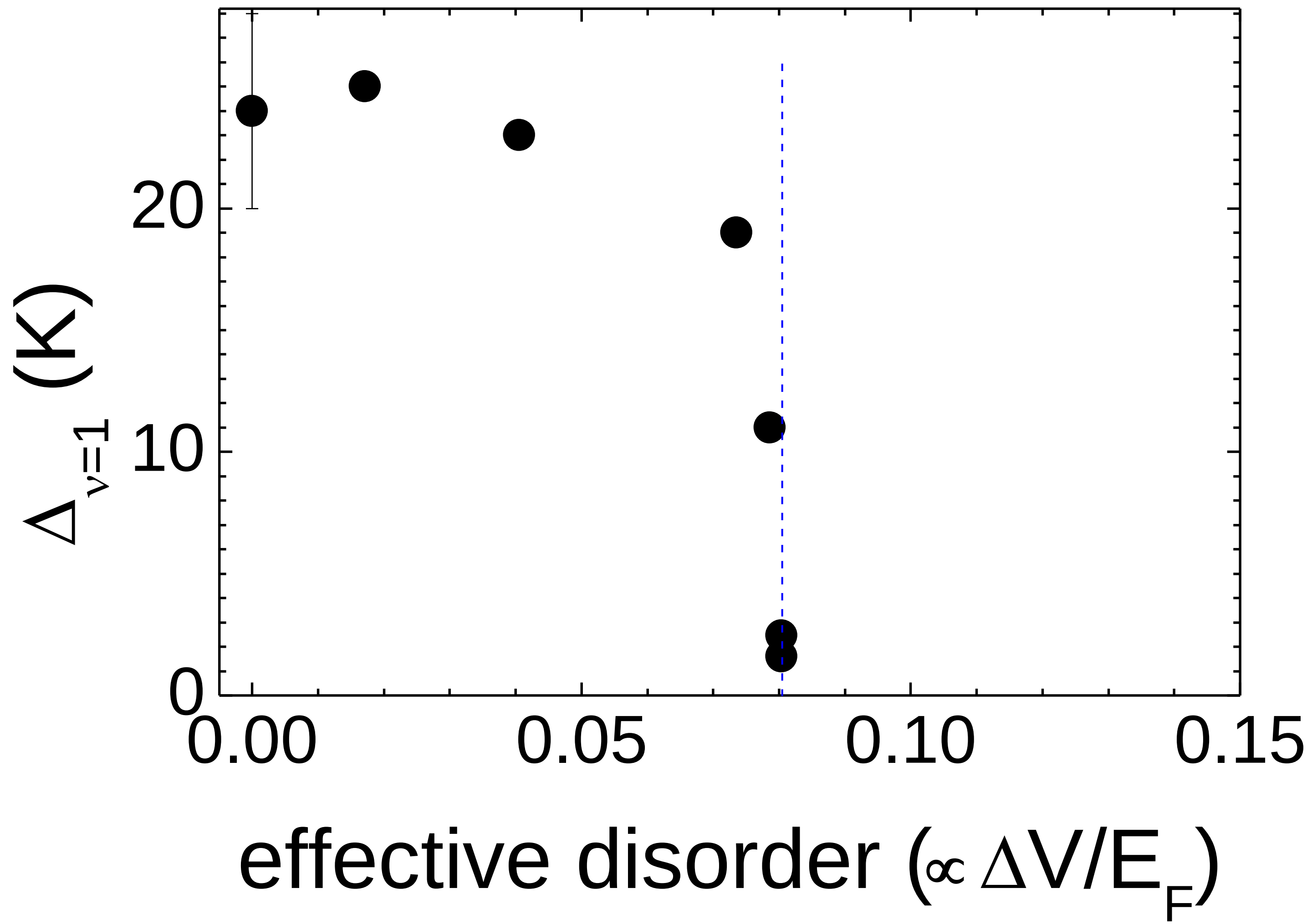
(Received 18 September 2001; published 2 January 2002)

We study quantum Hall ferromagnets in the presence of a random electrostatic impurity potential. Describing these systems with a classical nonlinear sigma model and using analytical estimates supported by results from numerical simulations, we examine the nature of the ground state as a function of disorder strength, Δ, and deviation, $\delta\nu$, of the average Landau level filling factor from unity. Screening of an impurity potential requires distortions of the spin configuration, and in the absence of Zeeman coupling there is a disorder-driven, zero-temperature phase transition from a ferromagnet at small Δ and $|\delta\nu|$ to a spin glass at larger Δ or $|\delta\nu|$. We examine ground-state response functions and excitations.

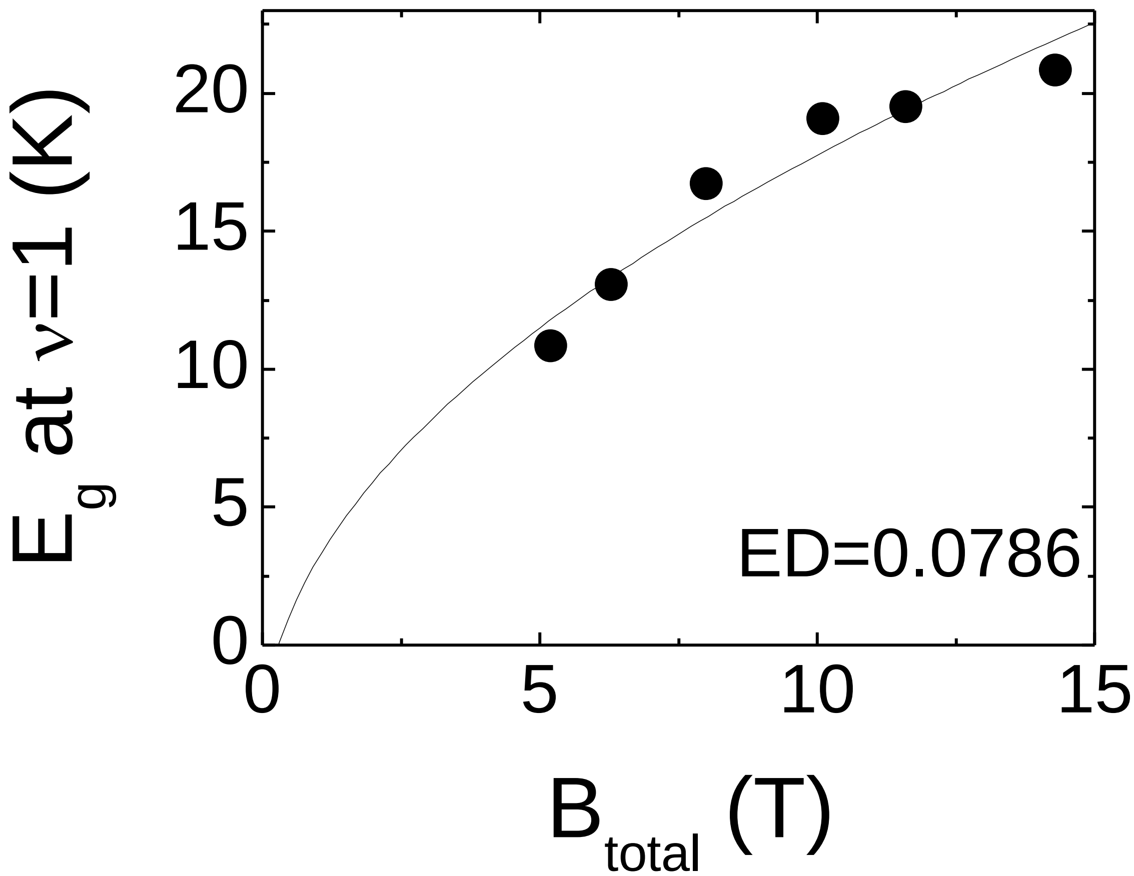


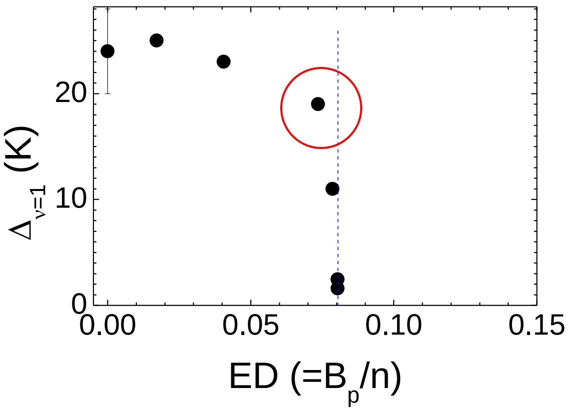
effective disorder → $\Delta V/E_F$



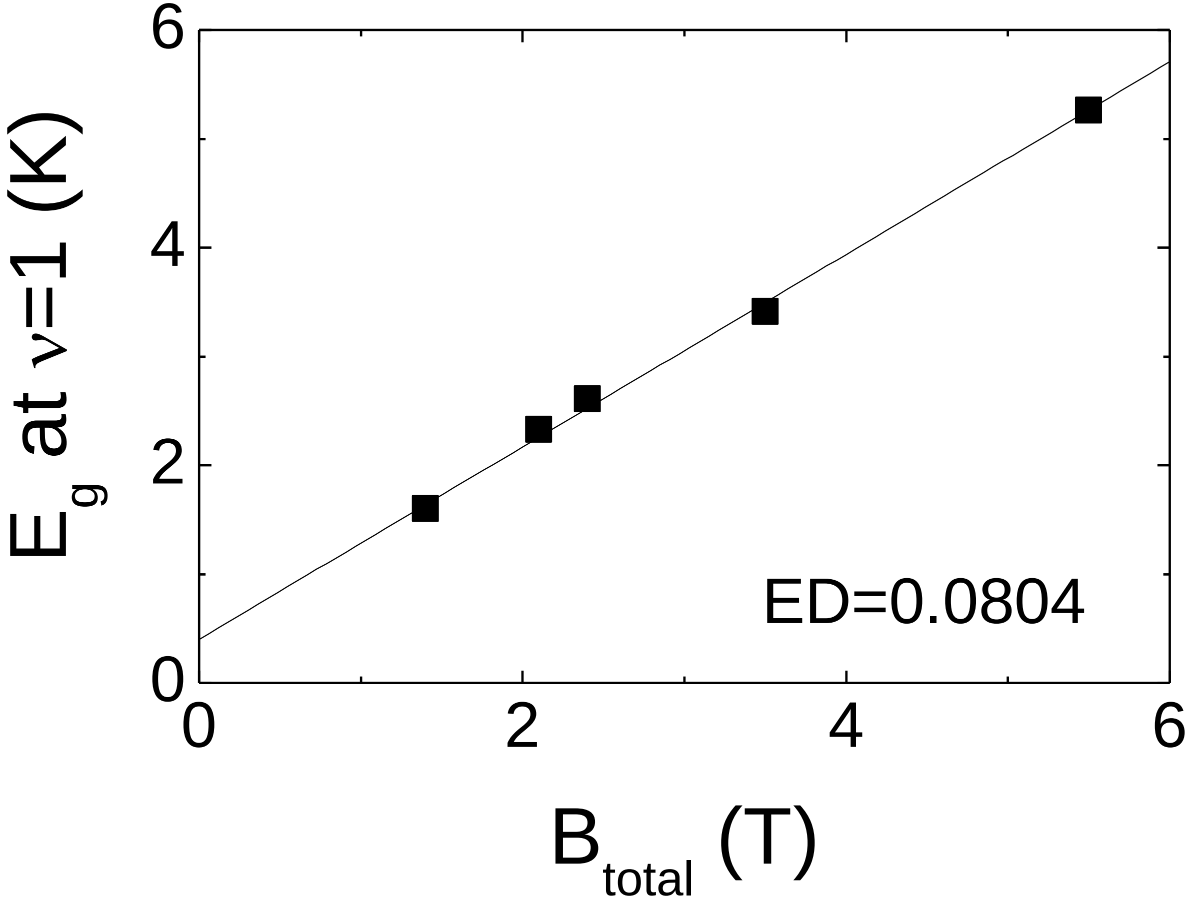


20
10
0
0.00
0.05
0.10
0.15
Δ_ν=1 (K)
effective disorder (∝ ΔV/E_F)

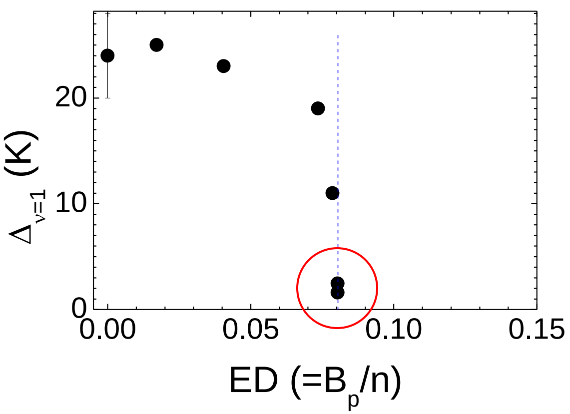




$$E_c = e^2/\varepsilon l_B \sim B^{1/2}$$



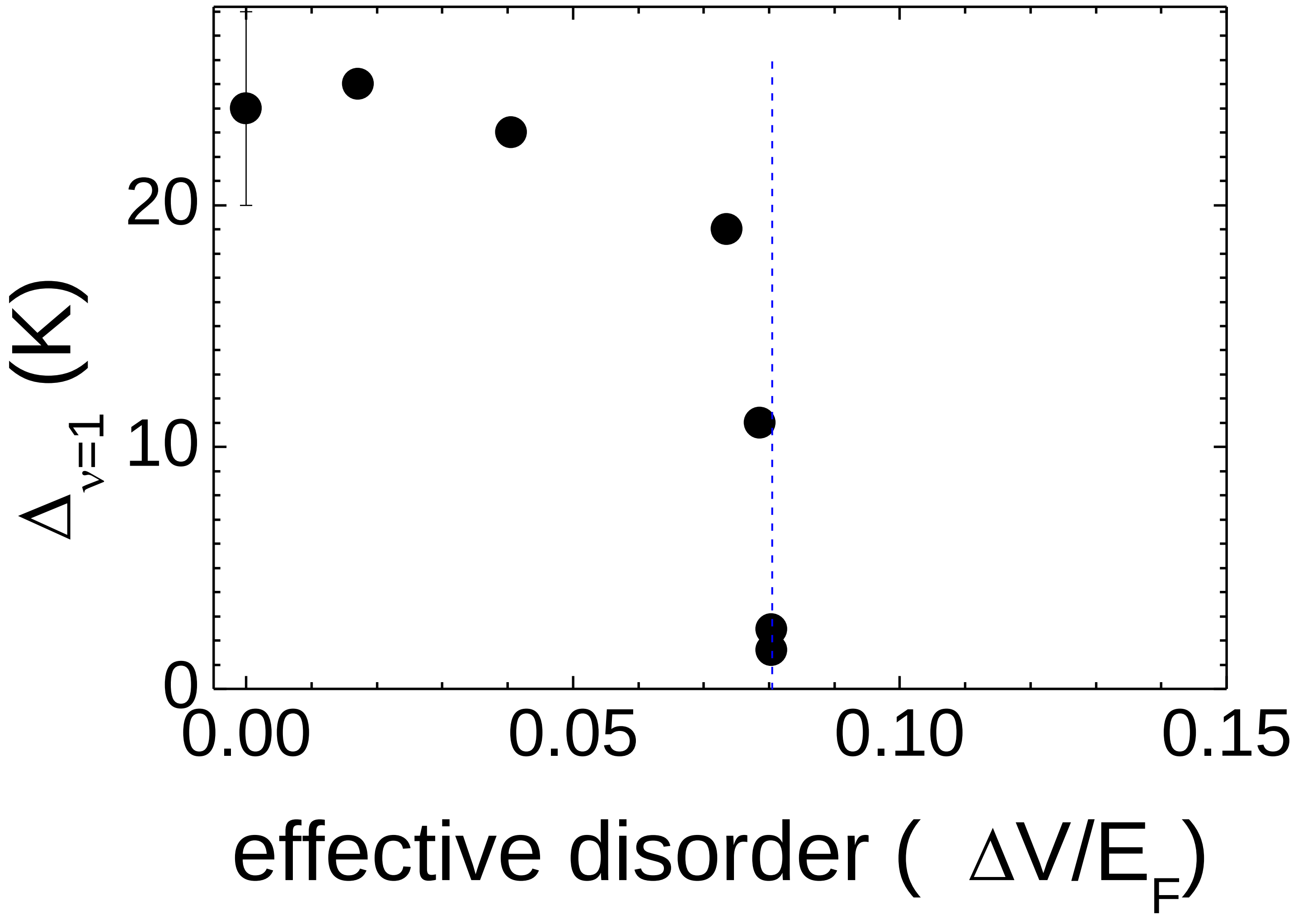
6
4
2
0
0
2
4
6
E_g at ν=1 (K)
B_{total} (T)
ED=0.0804



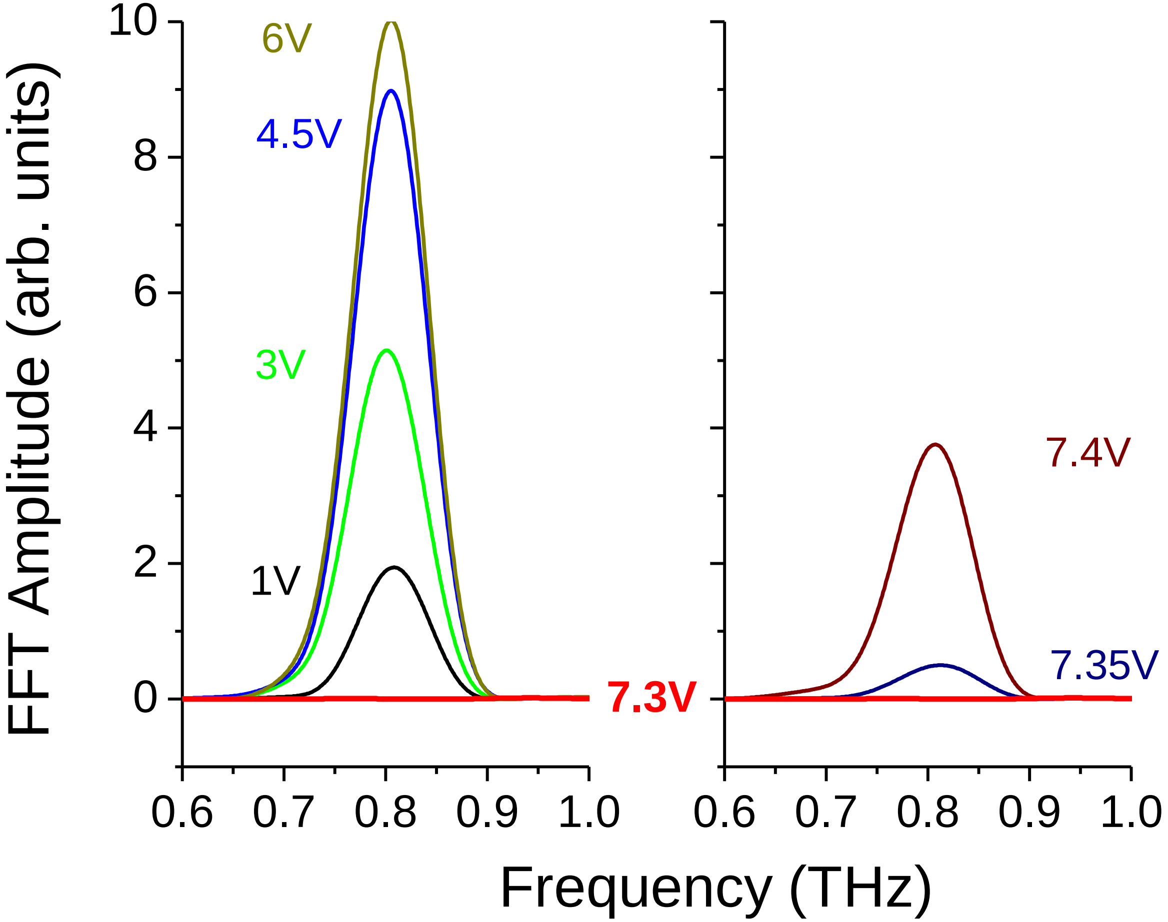
20
10
0
0.00
0.05
0.10
0.15
$\Delta_{\nu=1}$ (K)
ED (=B_p/n)

$$E_z = g^*\mu_B B$$

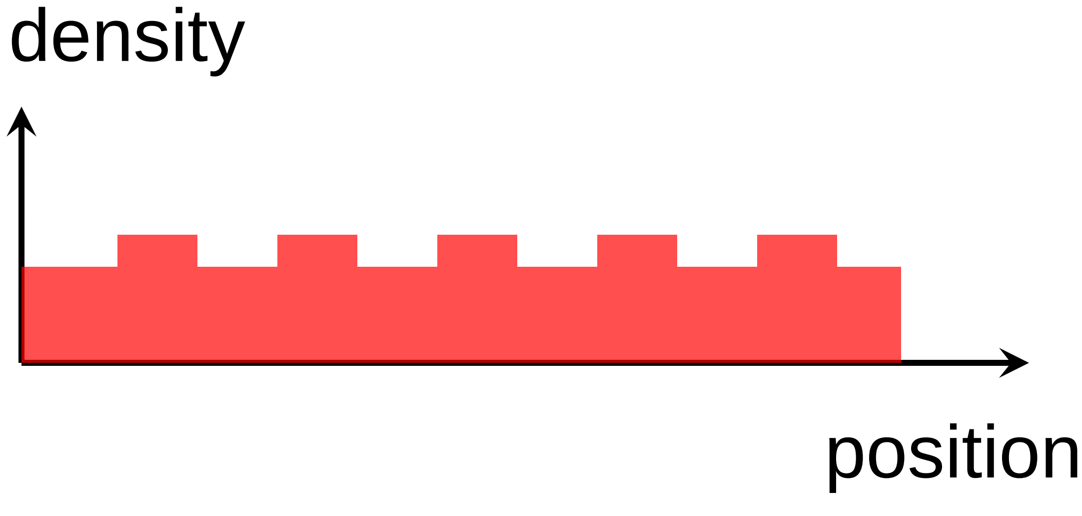
QH ferromagnetism to QH spin glass



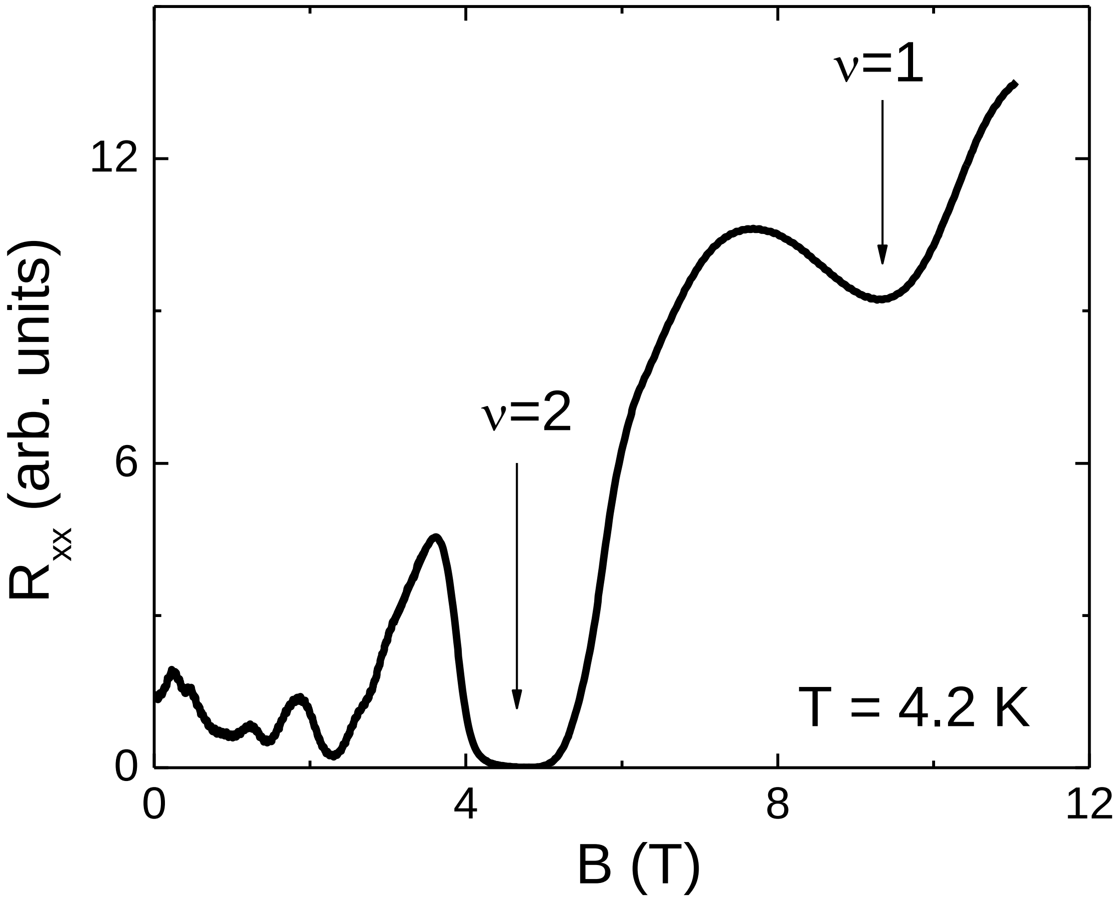
THz amplification?



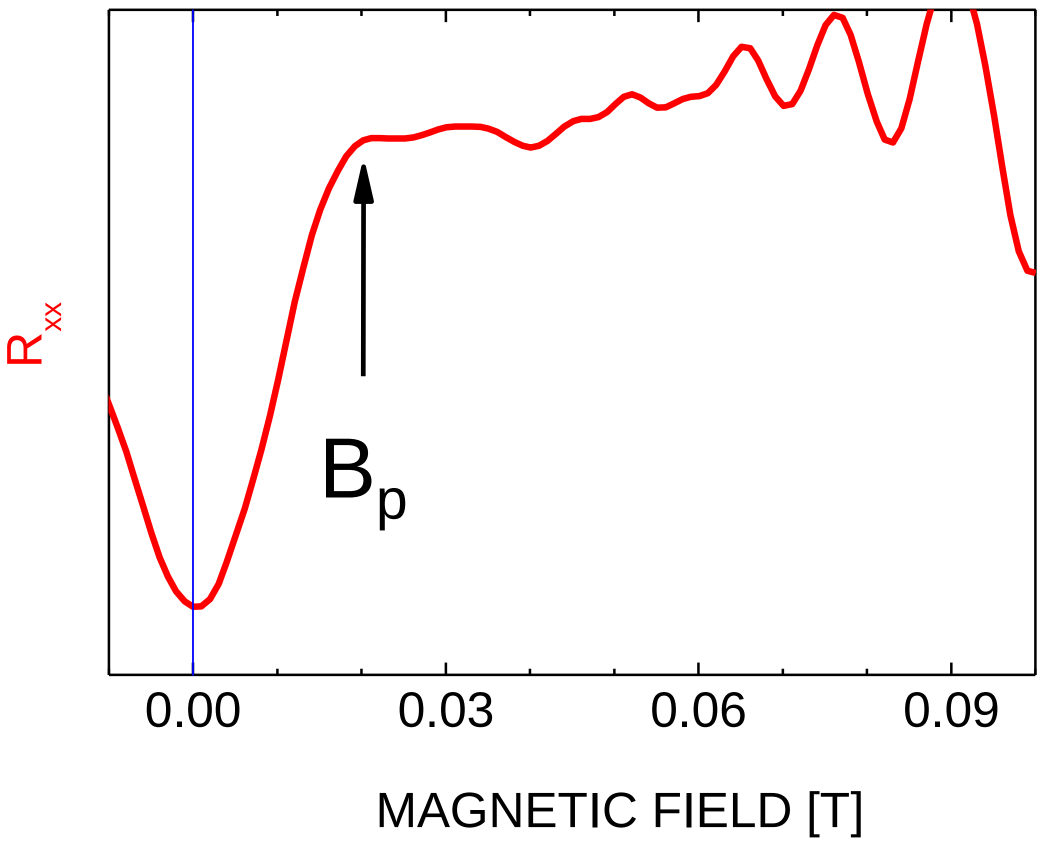
periodic density modulation



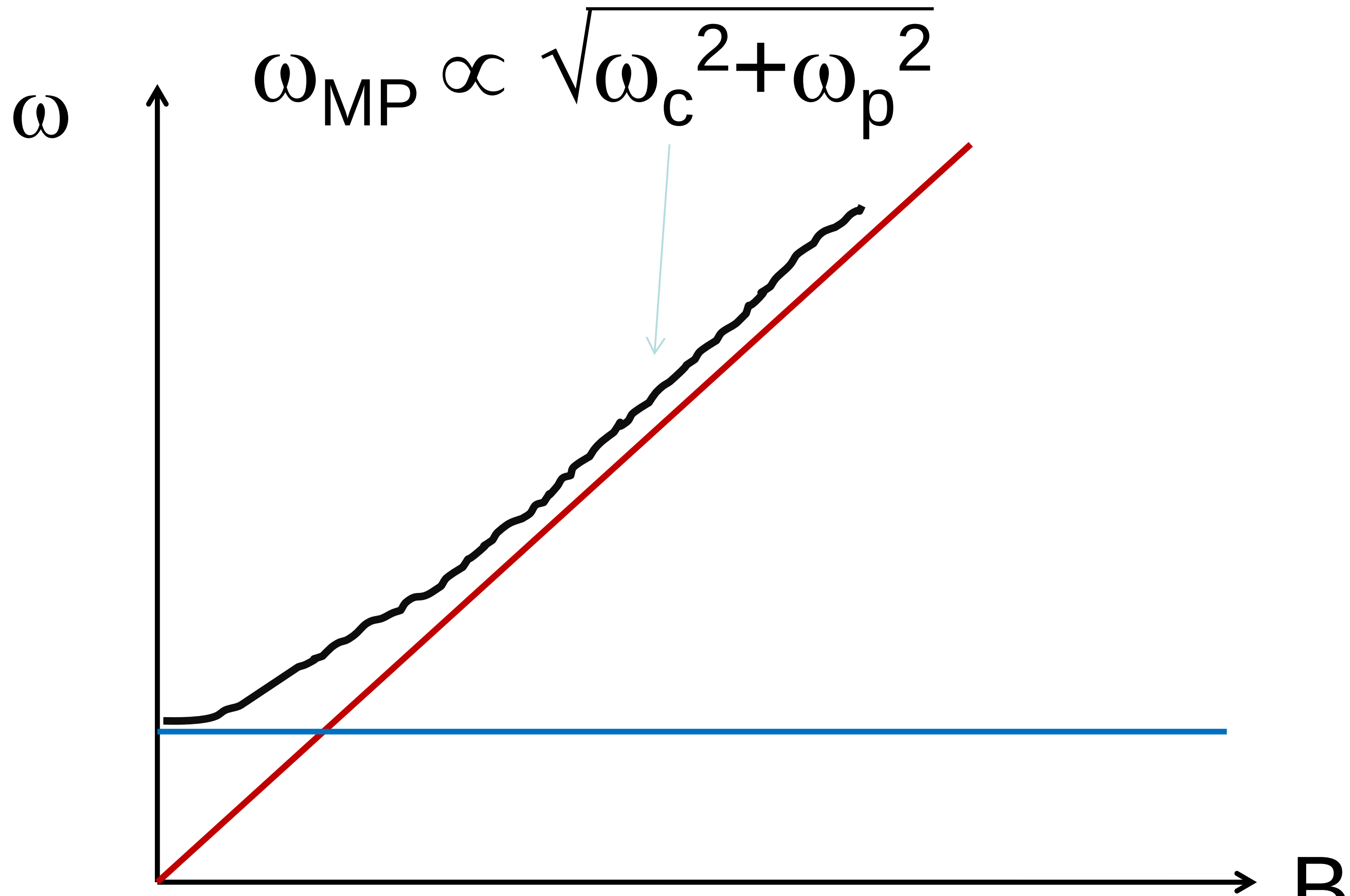
weak ν=1 integer quantum Hall state



antidot array sample

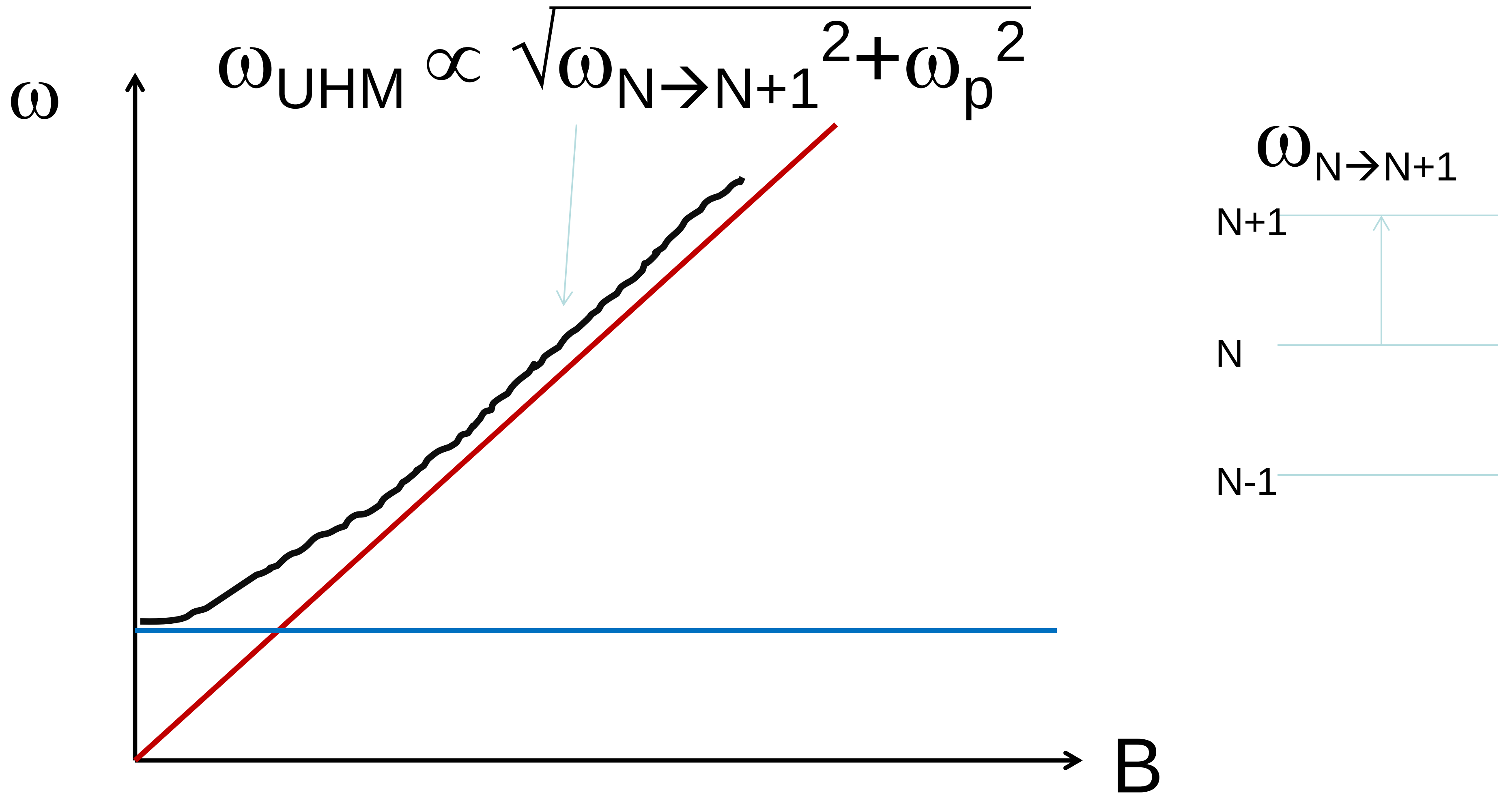


Beton et al, PRB 42, 9229 (1990)



Conventional 2DEG – $\omega_c \propto B$

Dirac 2DEG – $\omega_c \propto B^{1/2}$


ω
ω_UHM ∝ √(ω_N→N+1² + ω_p²)
B
ω_N→N+1
N+1
N
N-1