SAND2013-2813P

Bloch Oscillations in Two-Dimensional Antidot Arrays

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Basic Energy Sciences

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outline

part I – Bloch oscillations in two-dimensional antidot arrays

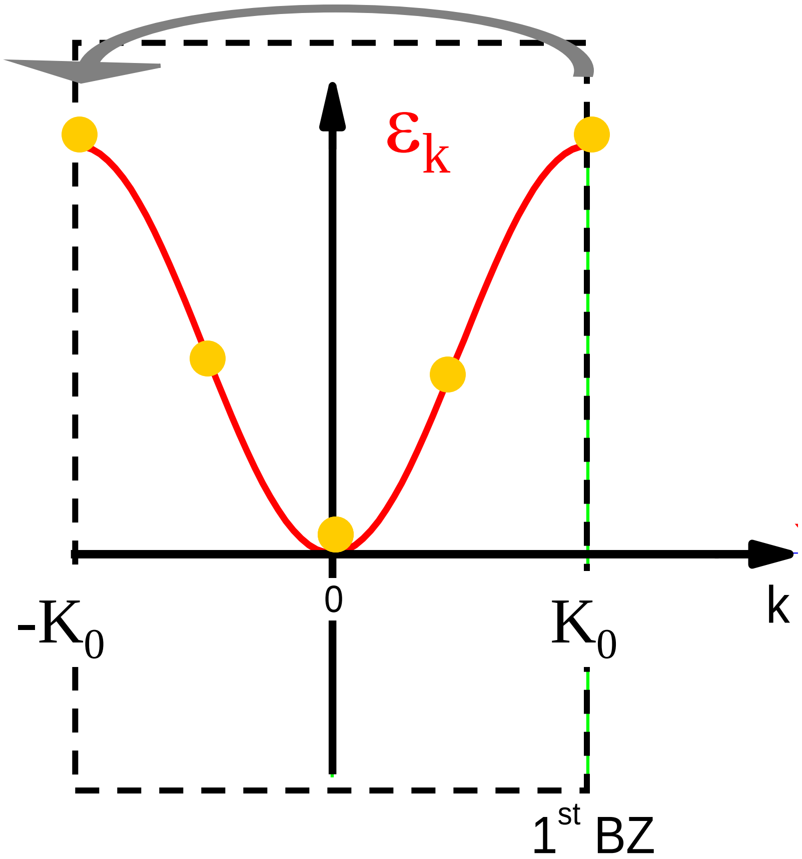
- motivation
- sample fabrication and characterization
- evidence of Bloch oscillations

part II – anomalous circular conductivity law in two-dimensional topological insulator of InAs/GaSb

part I – Bloch oscillations in two-dimensional arrays

what is Bloch oscillation?

Bloch, Z. Phys. 1928



Under a DC electric field E

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

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

$$\boldsymbol{\hbar\, dk/dt = eE}$$

$$\boldsymbol{k = eEt/\hbar}$$

$$\boxed{\begin{array}{c} \varepsilon_k \sim 1-\cos(ak) \\ v \sim \partial\varepsilon_k/\partial k \sim \sin(aeEt/\hbar) \\ \boldsymbol{r \sim \cos(aeEt/\hbar) = \cos(2\pi ft)} \end{array}}$$

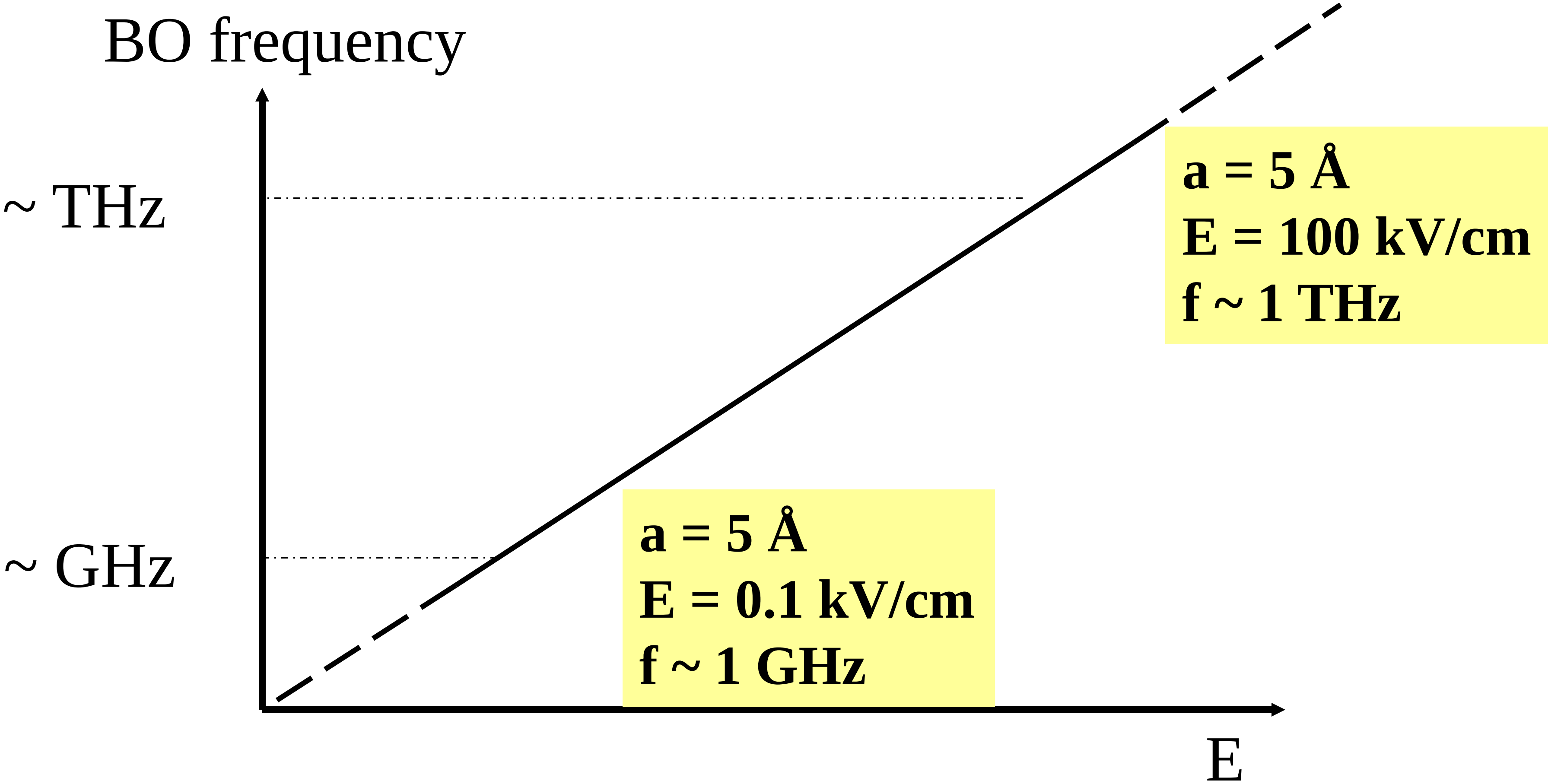
$$\boldsymbol{f = aeE/h}$$

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

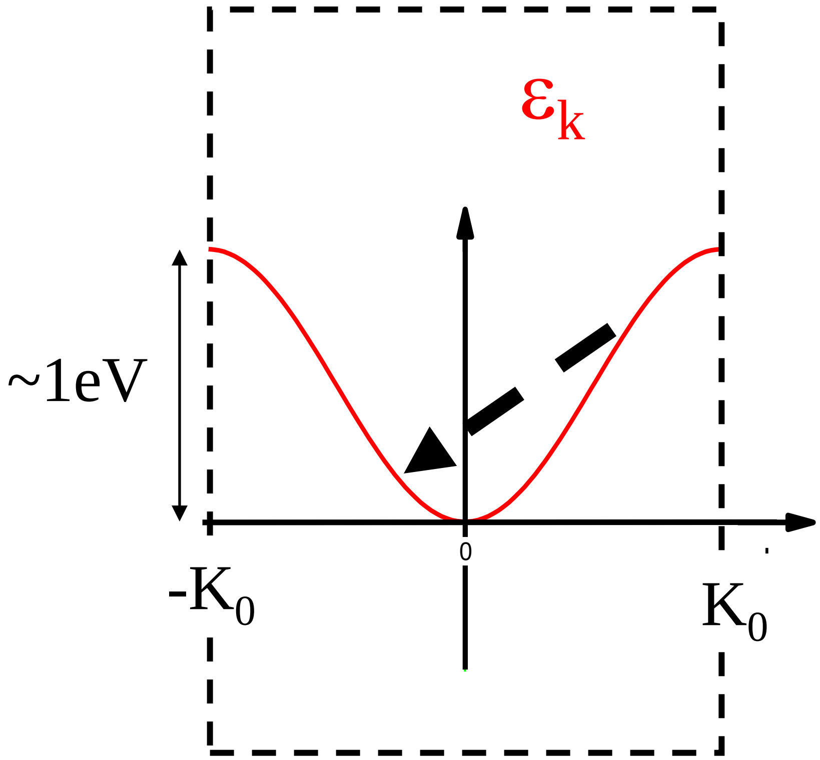
why Bloch oscillations (BO) ?

- THz application – frequency tunable

$$f = aeE/h$$



issues in 3D crystal



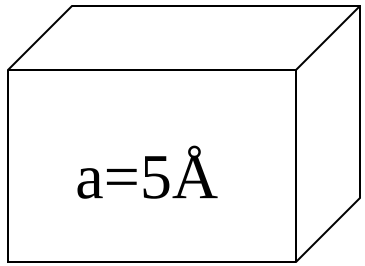
- Very high electric field

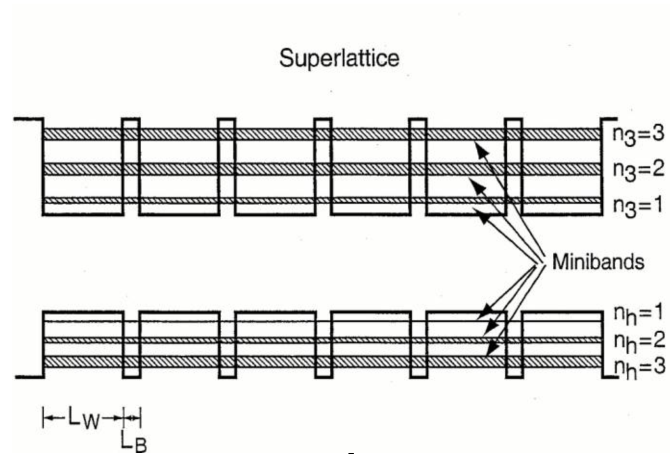
- Electron is scattered before it can complete a full oscillation

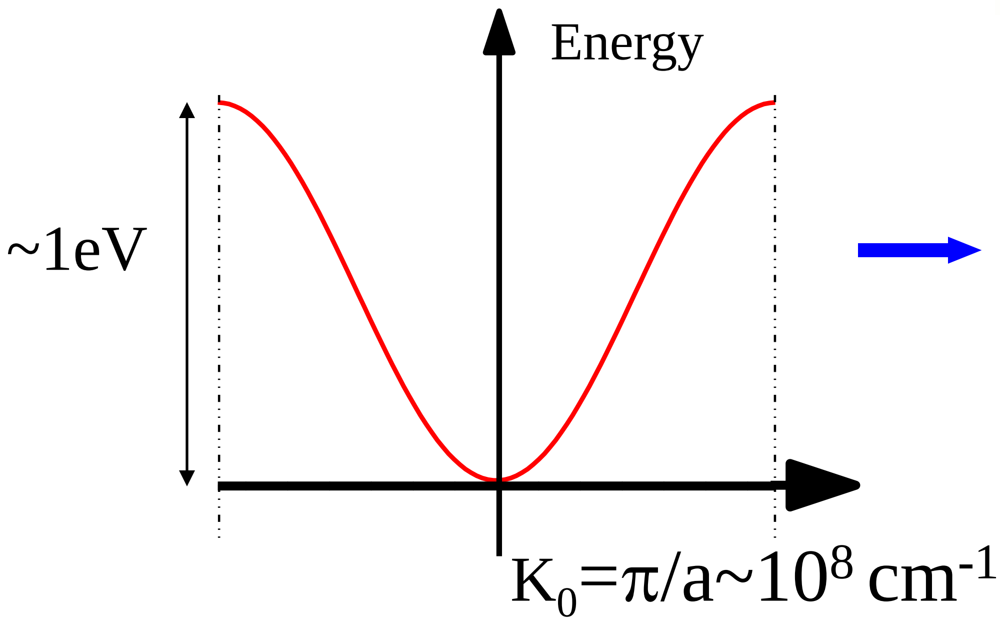
1D vertical superlattice

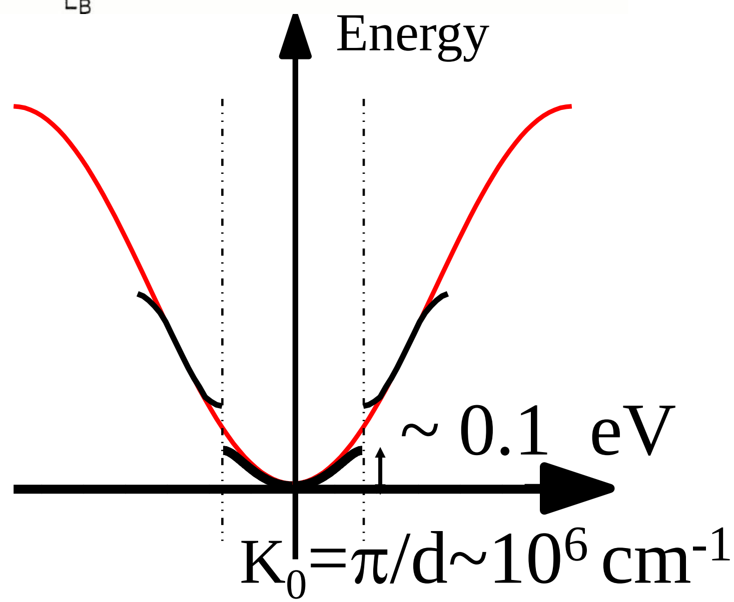
Esaki and Tsu, 1975

3D crystal









issues in 1D vertical superlattice

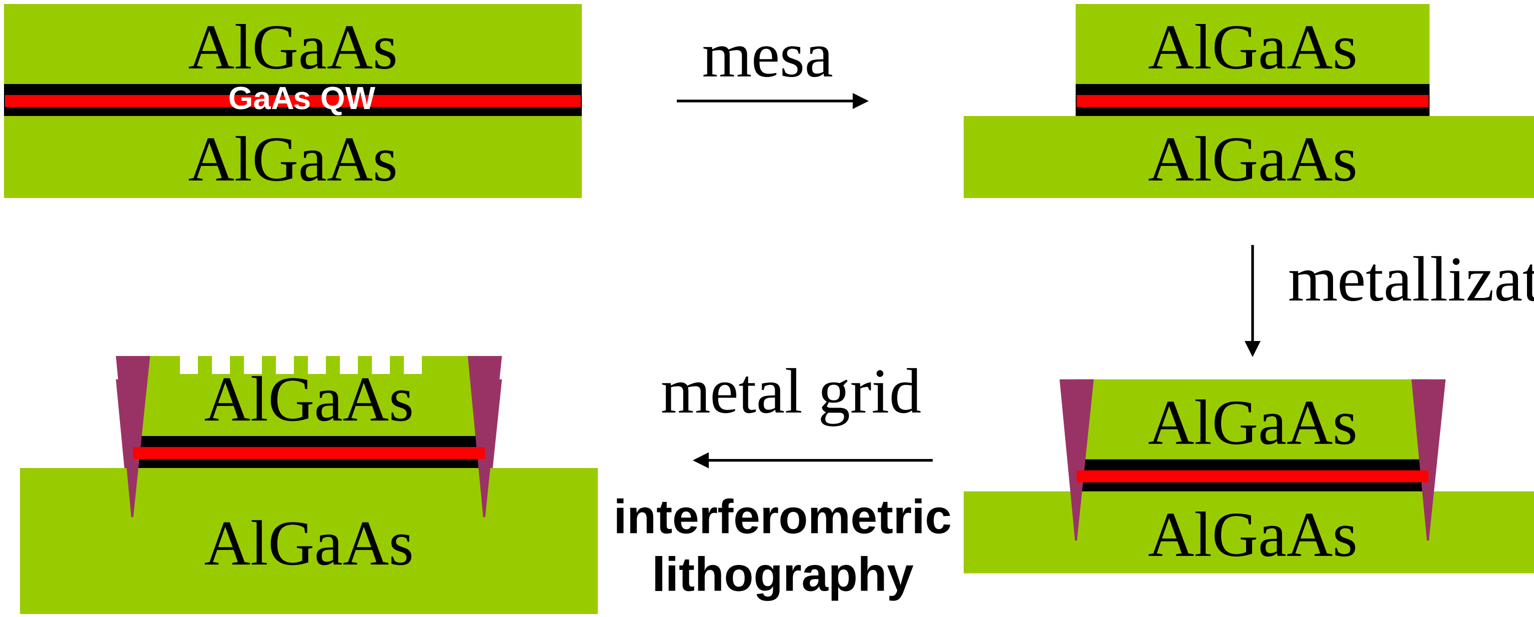
- formation of high electric field domains
- electron – phonon scattering
- impurity scattering
  - surface roughness scattering
- ….

2D quantum "dot" superlattice (QDSL)

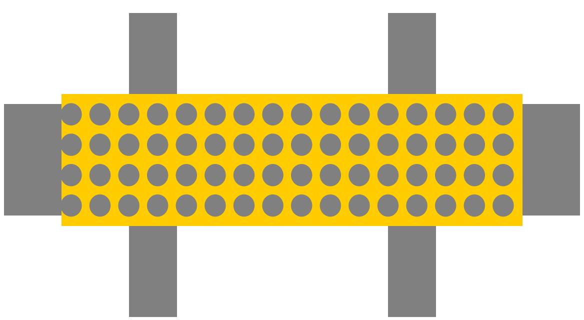
G.J. Iafrate, D.K. Ferry, and R.K. Reich, Surface Science 113, 485 (1982).
R. Reich, Ph.D. Thesis, Colorado State University at Fort Collins (1982).
G. Bernstein and D.K. Ferry, J. Vac. Sci. Tech. B 5, 964 (1987).
K. Ismail, et al, Appl. Phys. Lett. 54, 460 (1989).
I.A. Dmitriev and R.A. Suris, Semiconductors 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

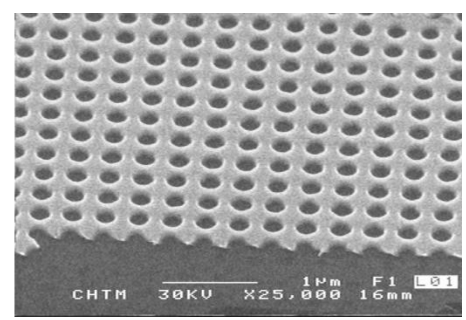
sample fabrication

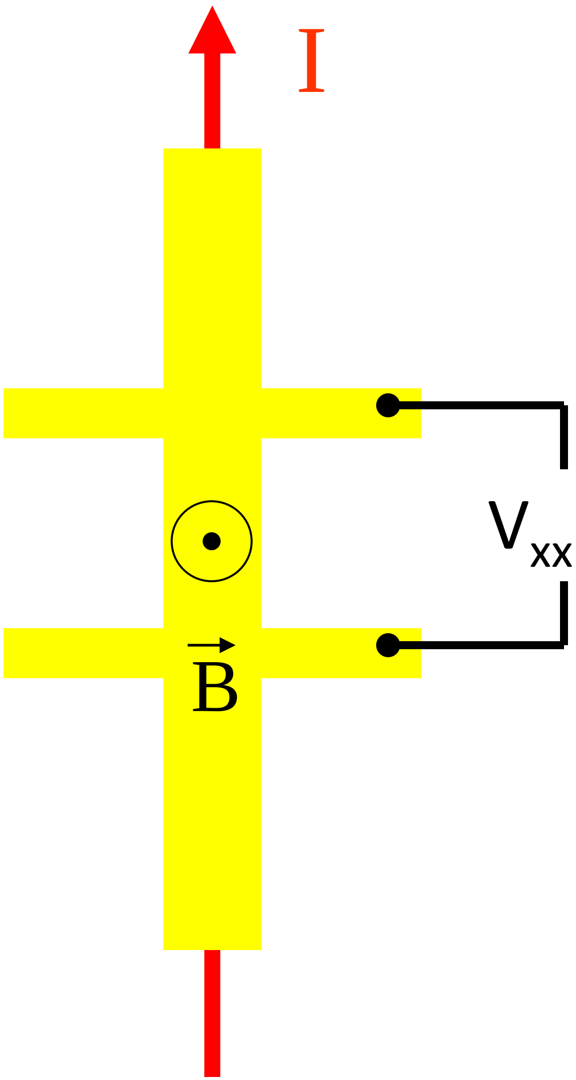


Top view



SEM picture

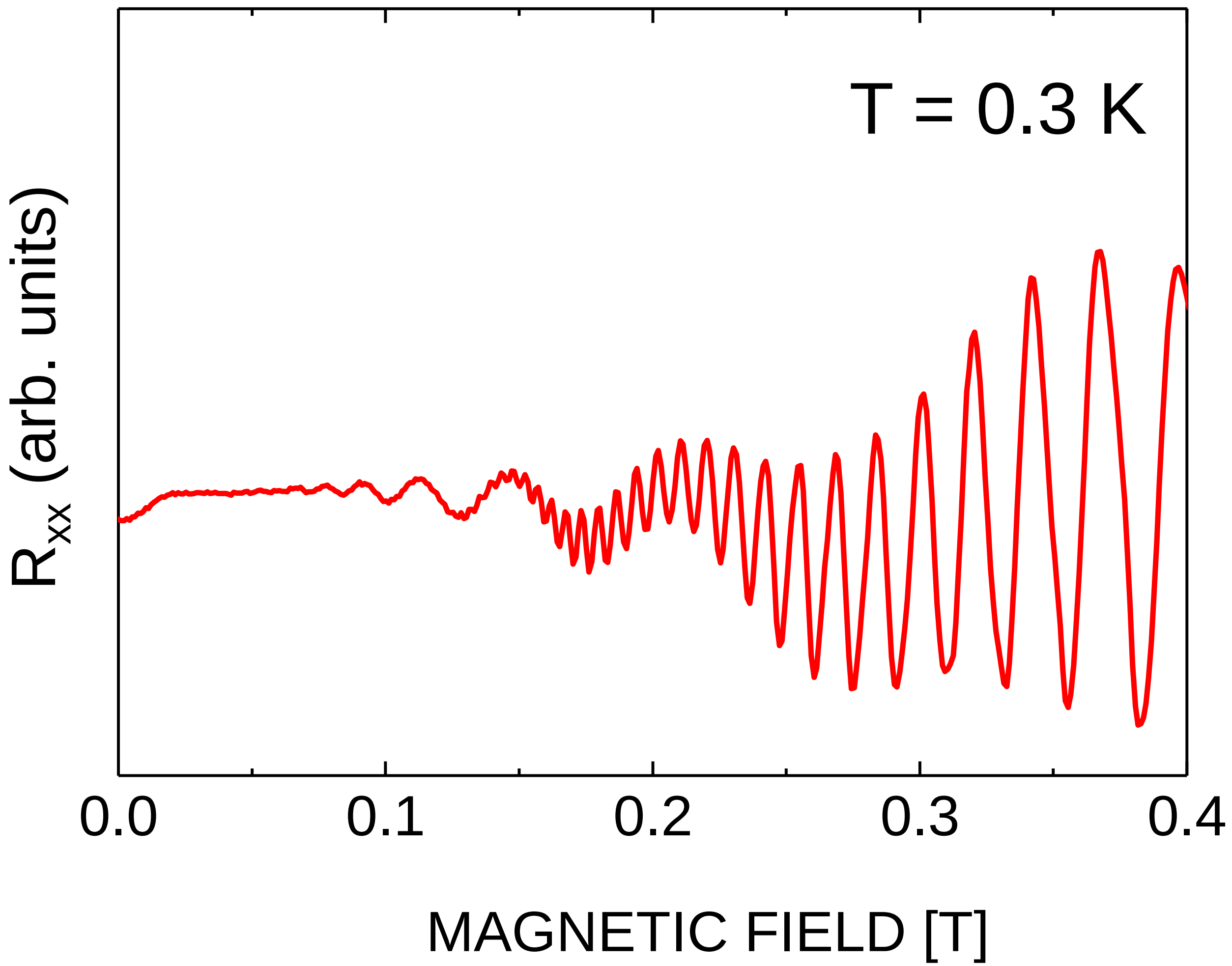


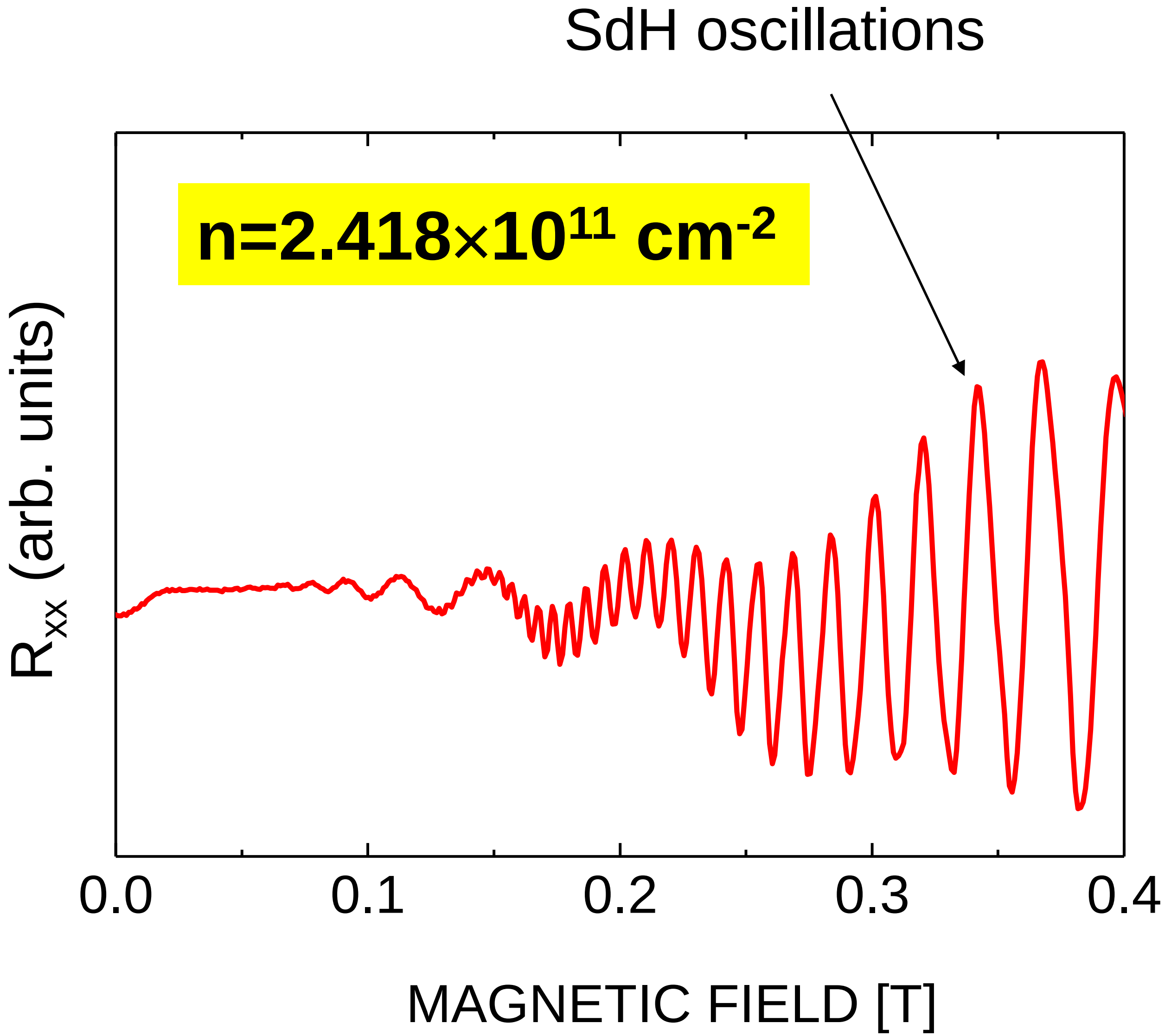


transport coefficients:

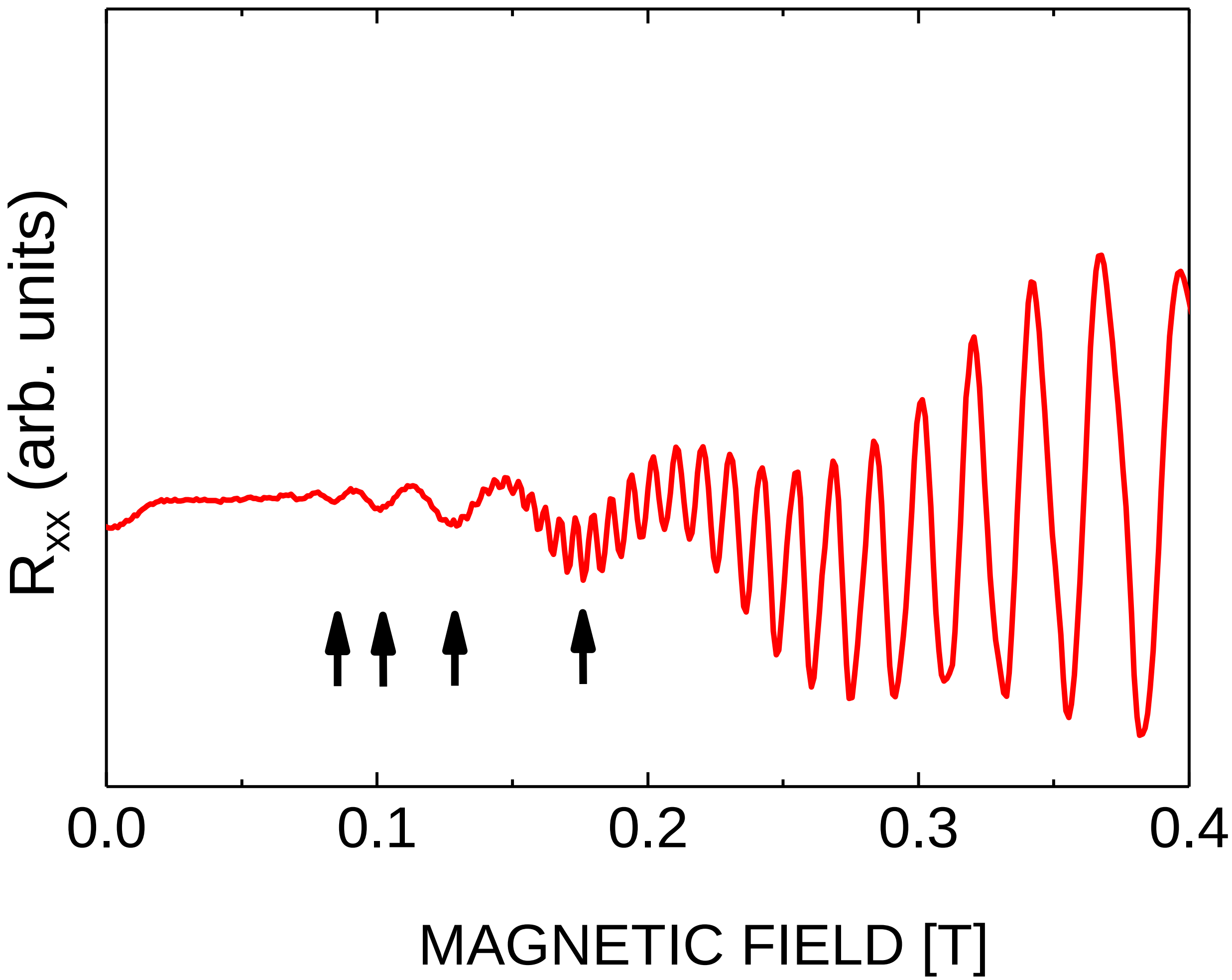
$$R_{xx} = V_{xx}/I$$

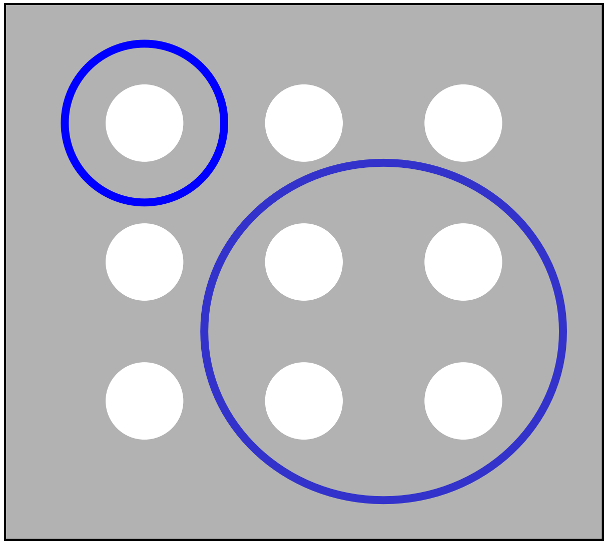
sample characterization – magneto-transport



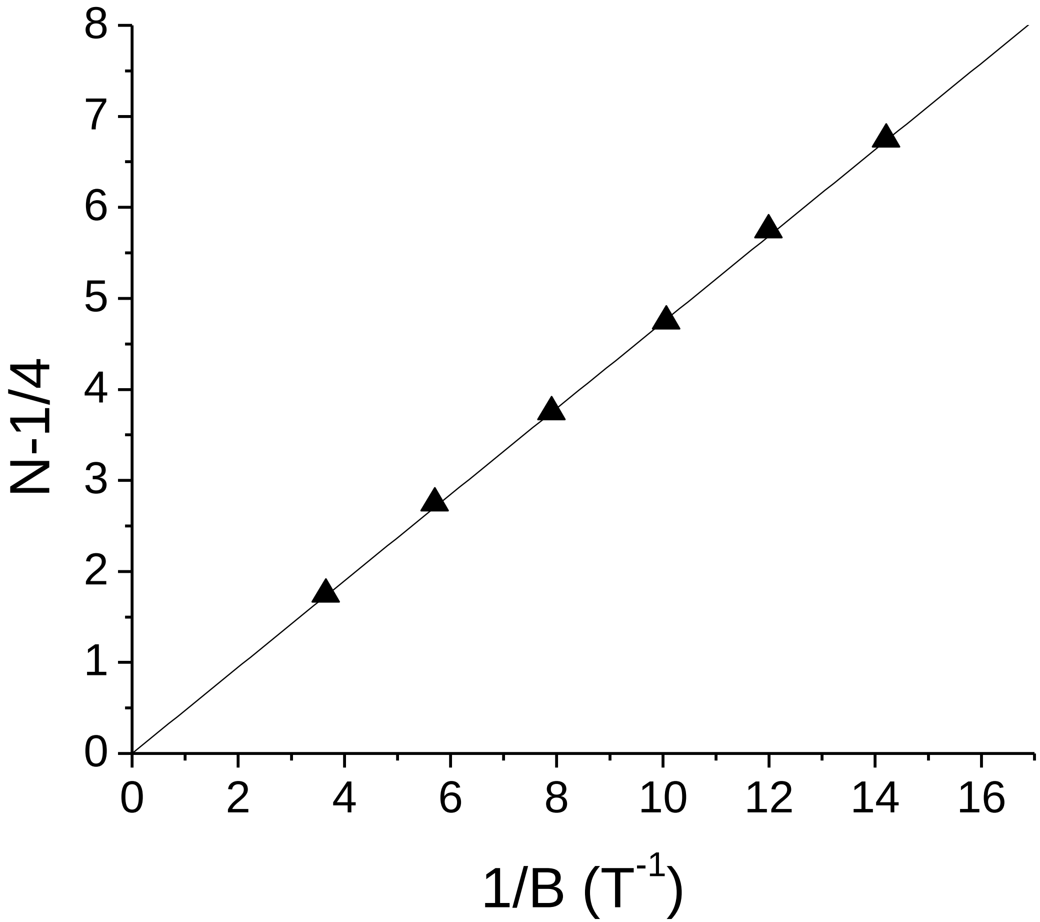

SdH oscillations
n=2.418×10^11 cm^-2
Rxx (arb. units)
0.0
0.1
0.2
0.3
0.4
MAGNETIC FIELD [T]

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

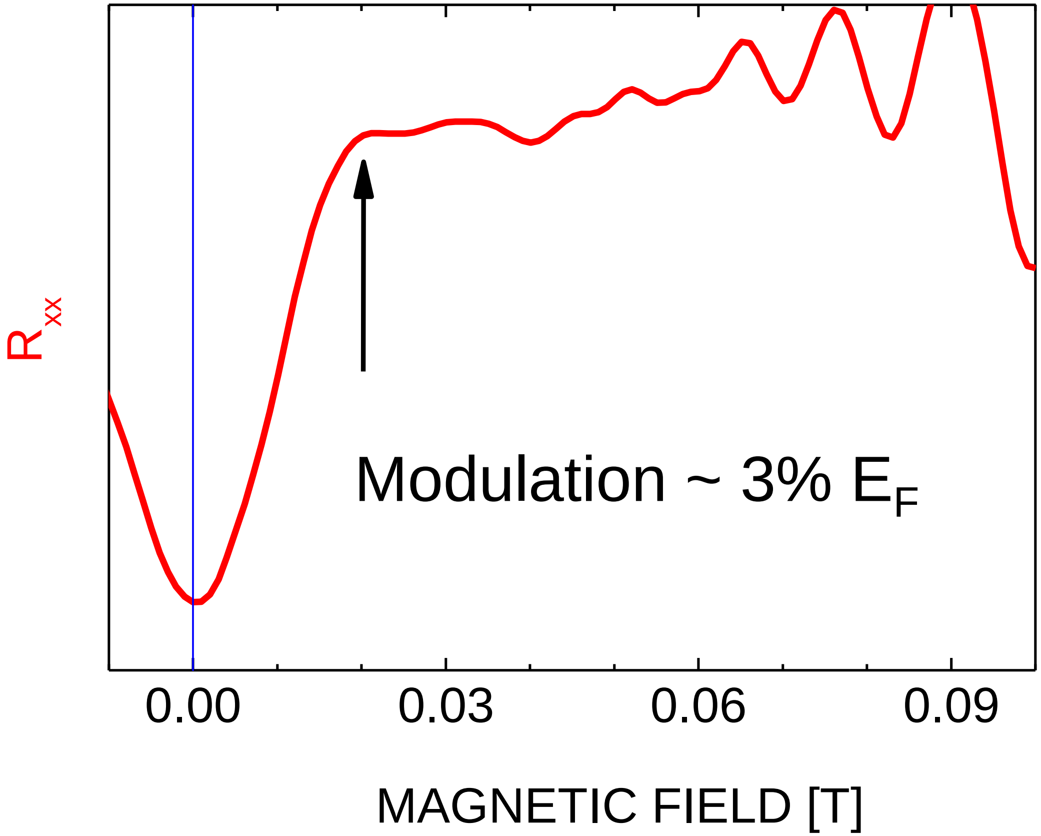
k_F – Fermi wavefactor

From slope,

d ~ 340 nm

Weiss et al, PRL 66, 2790 (1991)

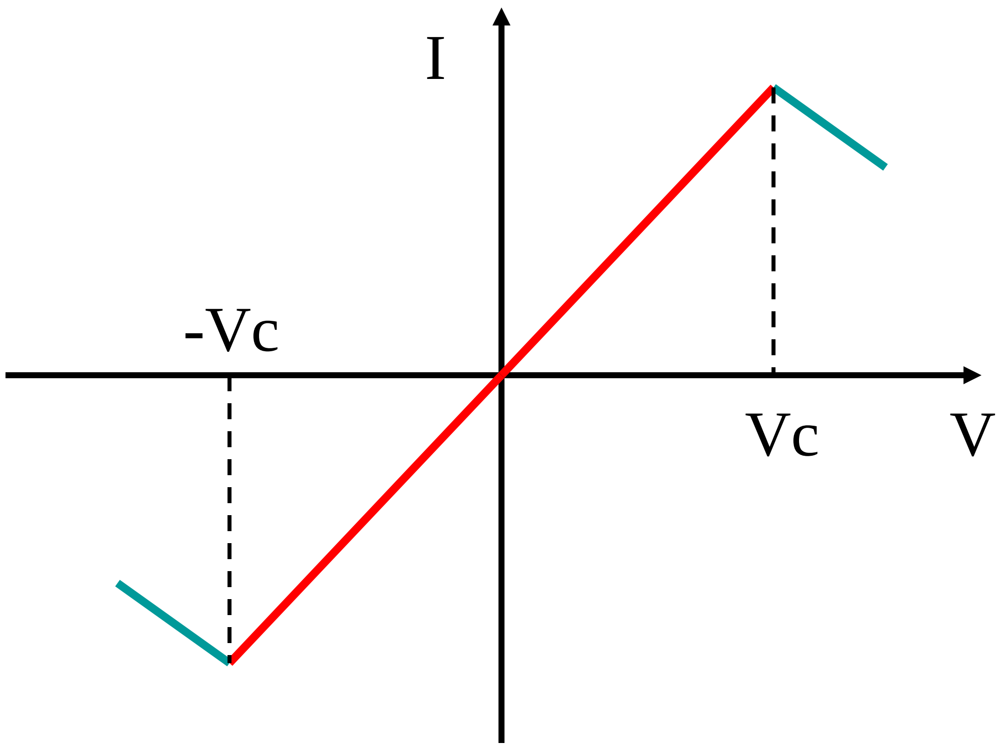
positive magneto-resistance around B = 0



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

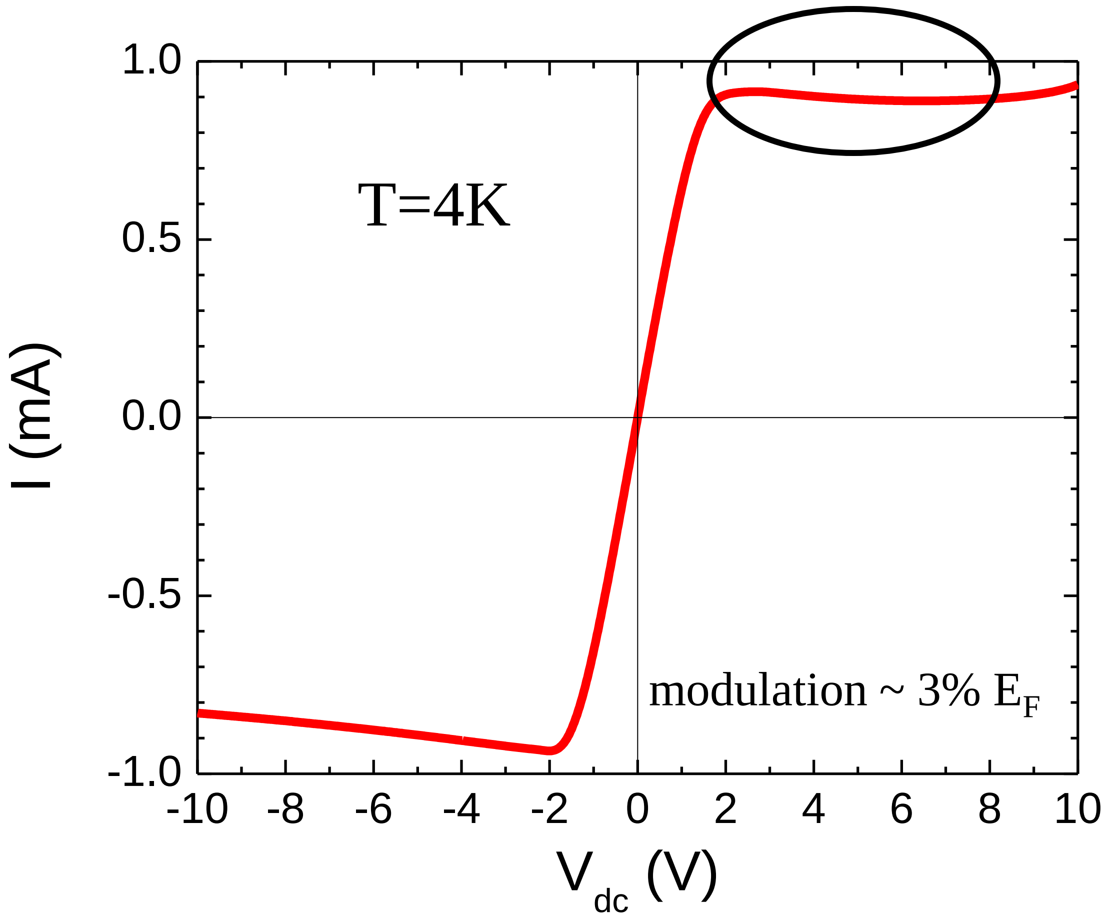
evidence of Bloch oscillations in 2D QDSL

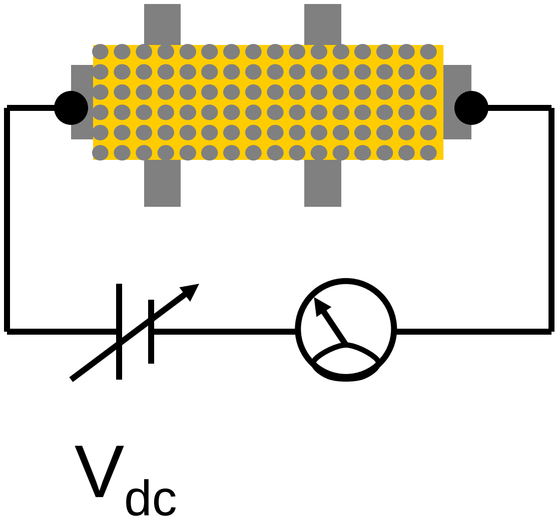
one of the signatures for Bloch oscillations is negative differential conductance (NDC)

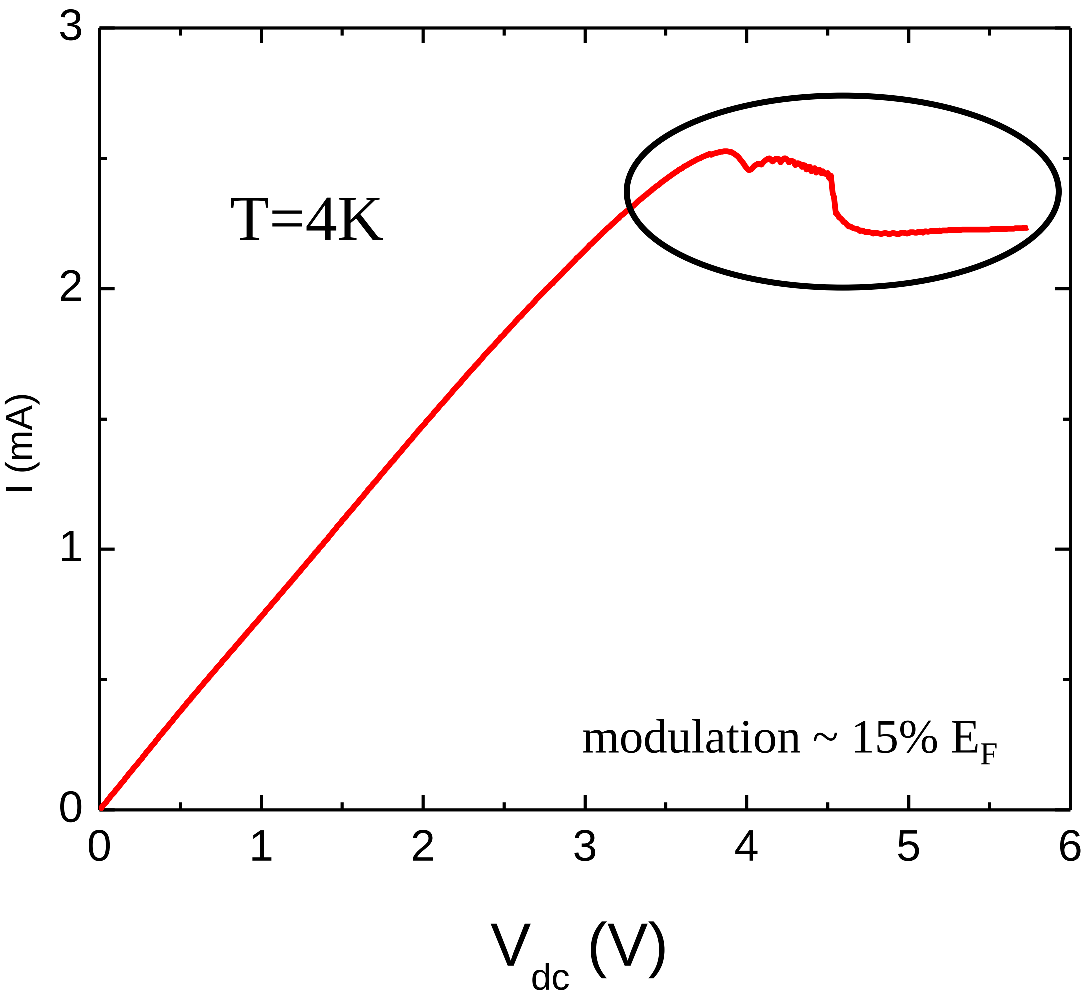


I – V measurement in 2D QDSL

NDC observed

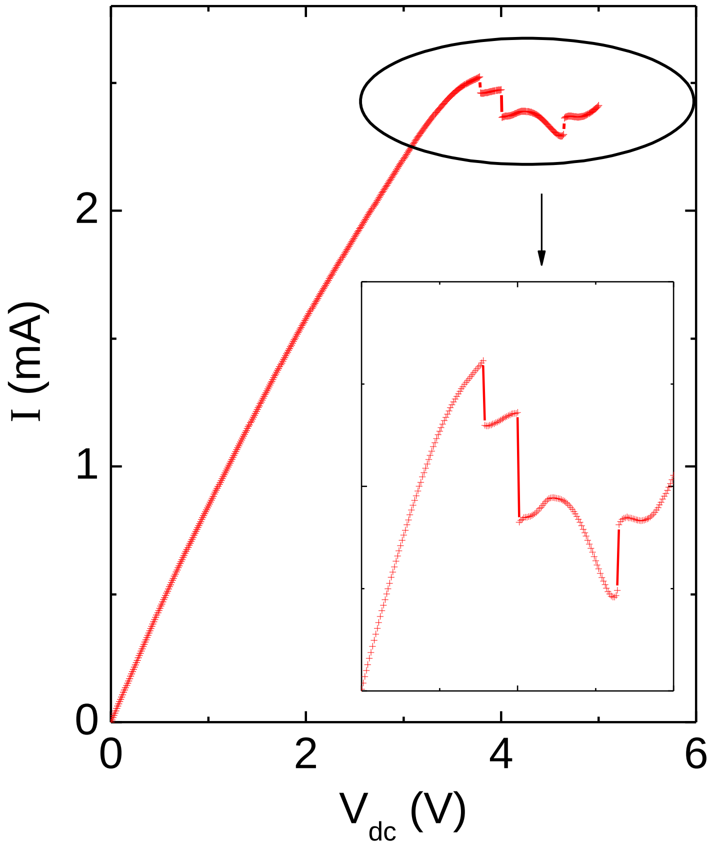






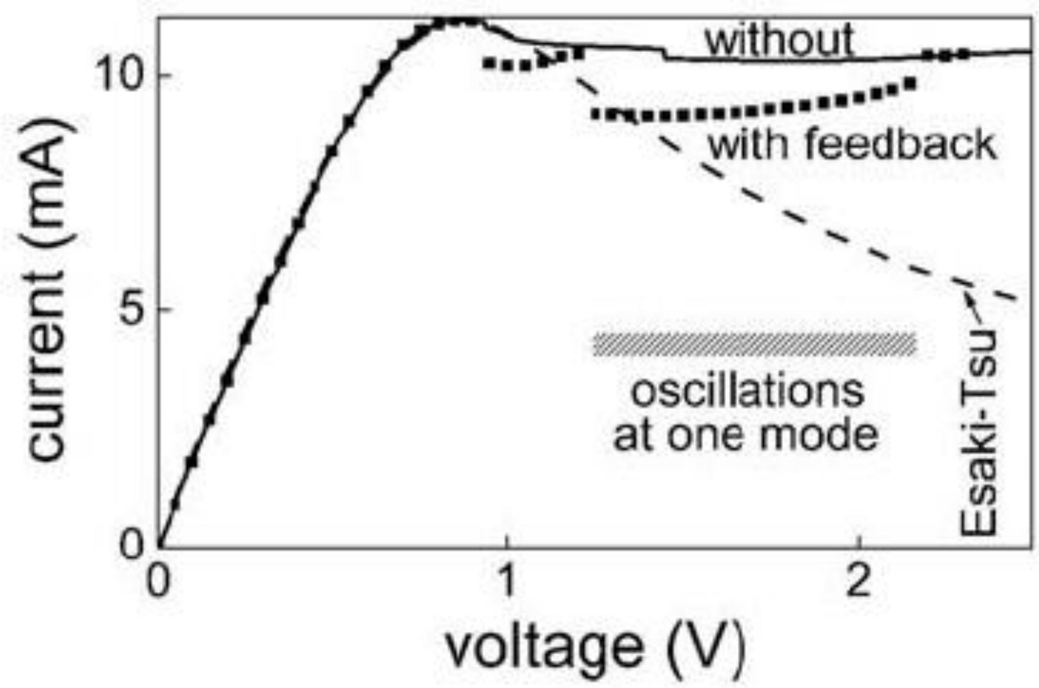
T=4K
modulation ~ 15% E_F
I (mA)
V_{dc} (V)
0
1
2
3
4
5
6

in yet another sample



Similar current jumps were also observed in:

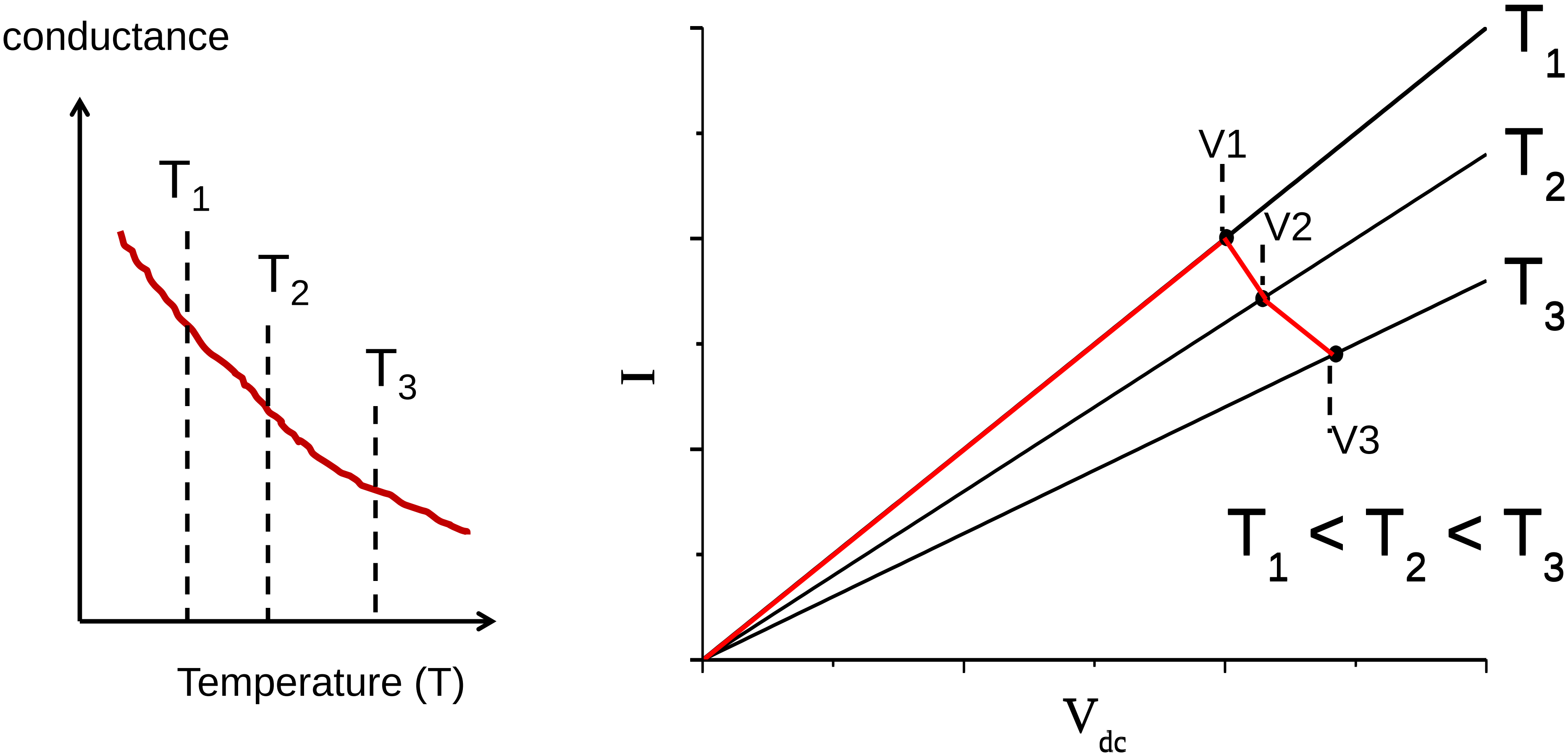
• **GaAs/AlAs 1D superlattices** (Renk et al, 2005)



physical origin of NDC ?

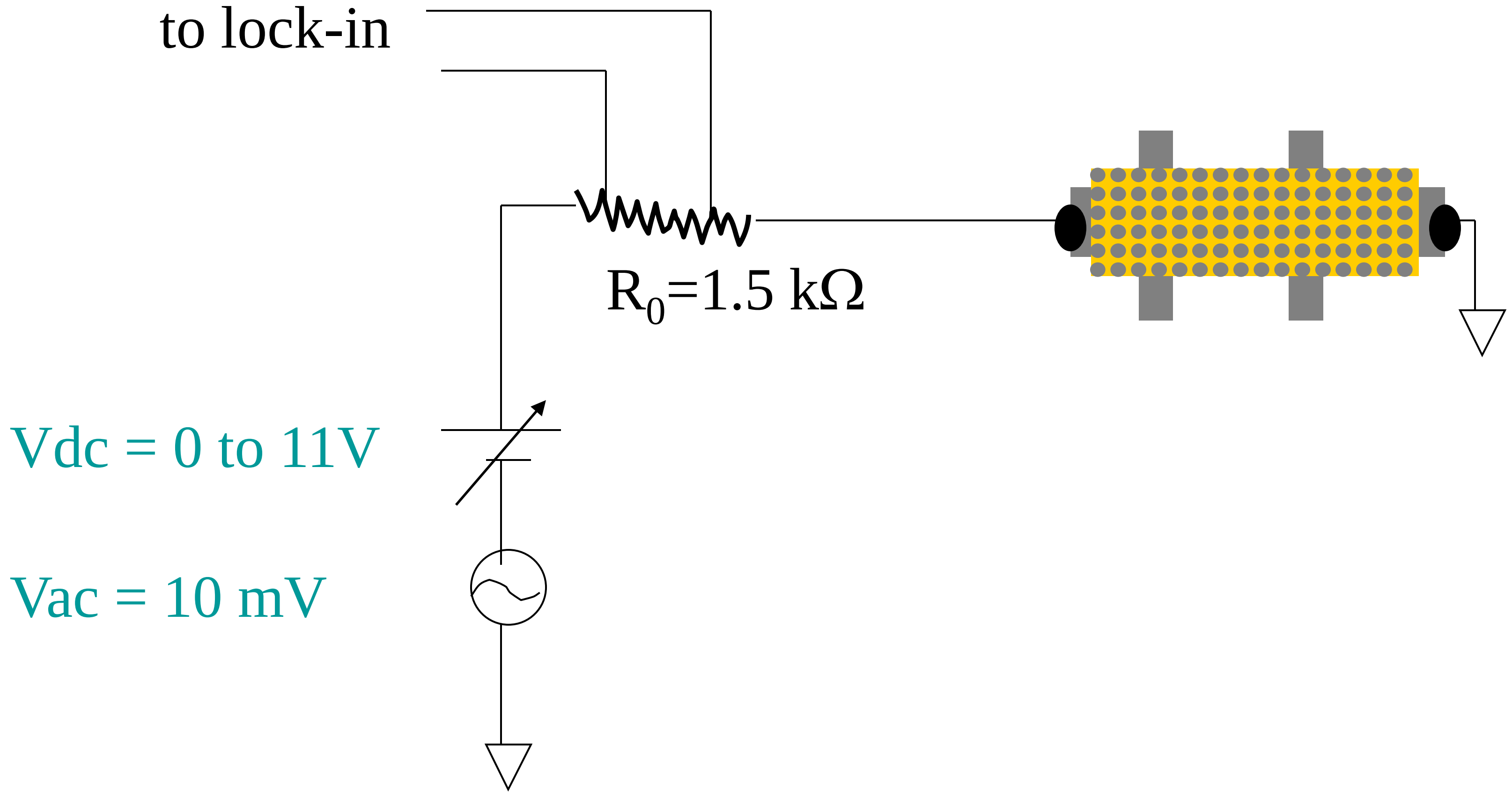
- Bloch oscillations?
- thermal runaway?
- ….

thermal runaway



Temperature dependent conductance can give rise to an apparent NDC

(Suggested by Mark Lee)

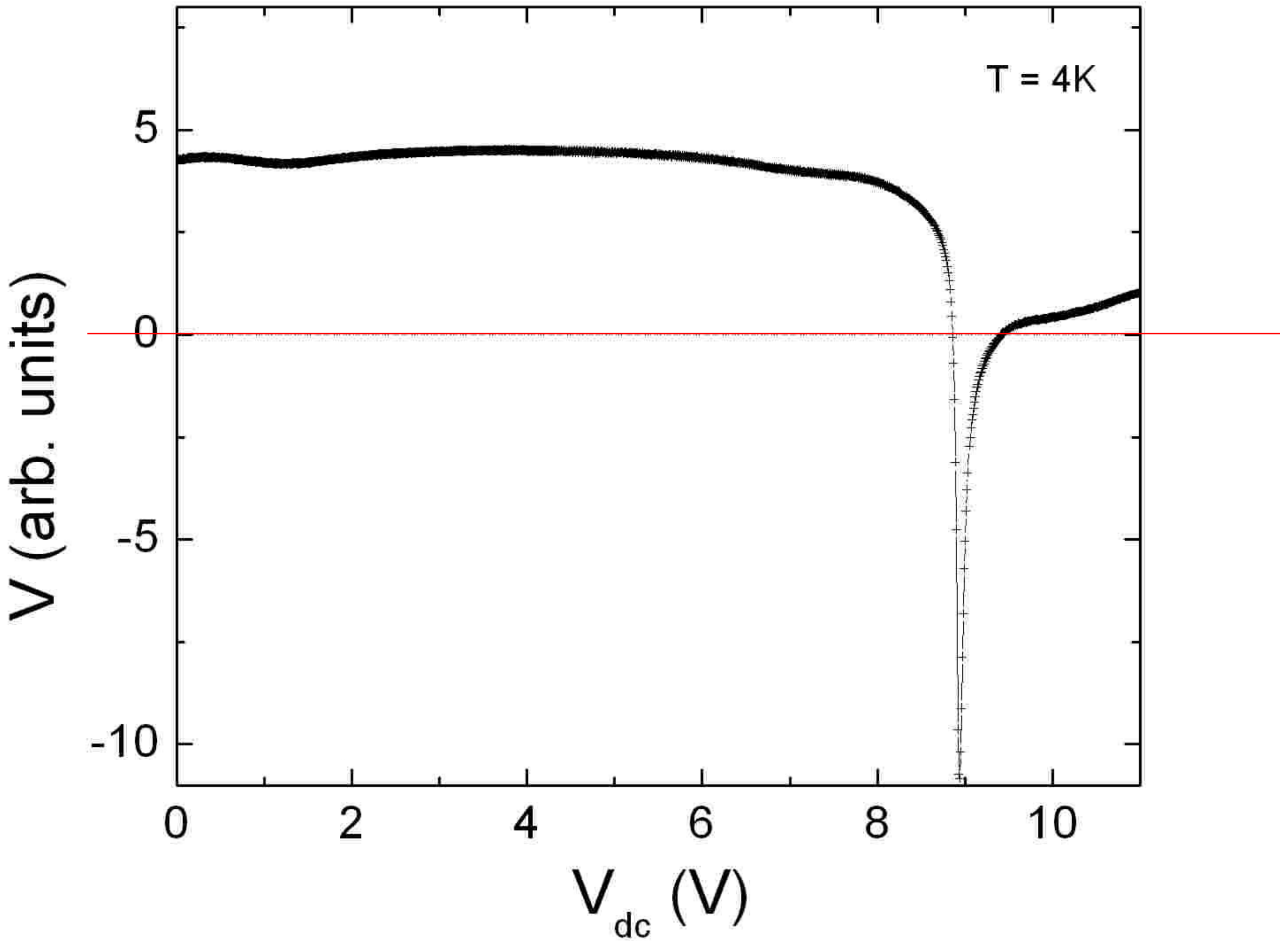


$V_{\text{lock-in}} = R_0/(R_0+r) \times \text{Vac}$

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

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

true negative differential conductance

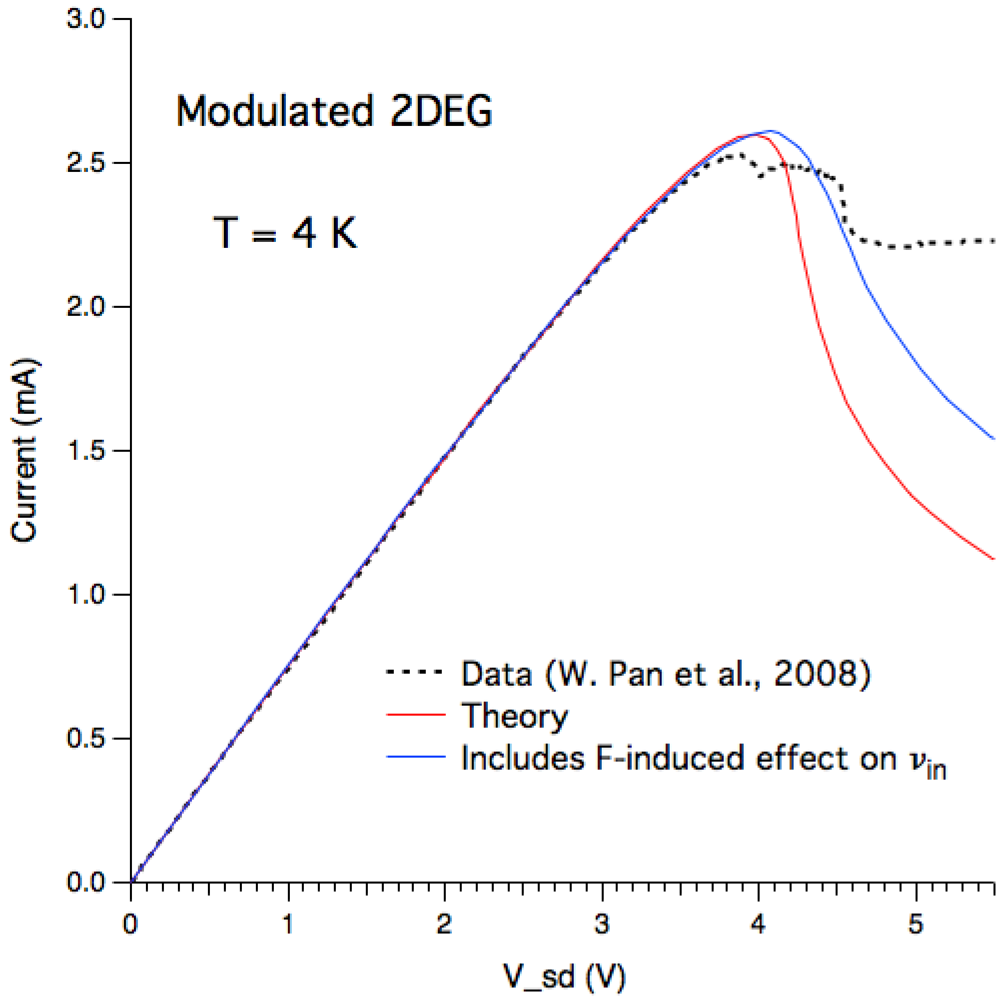


physical origin of NDC ?

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

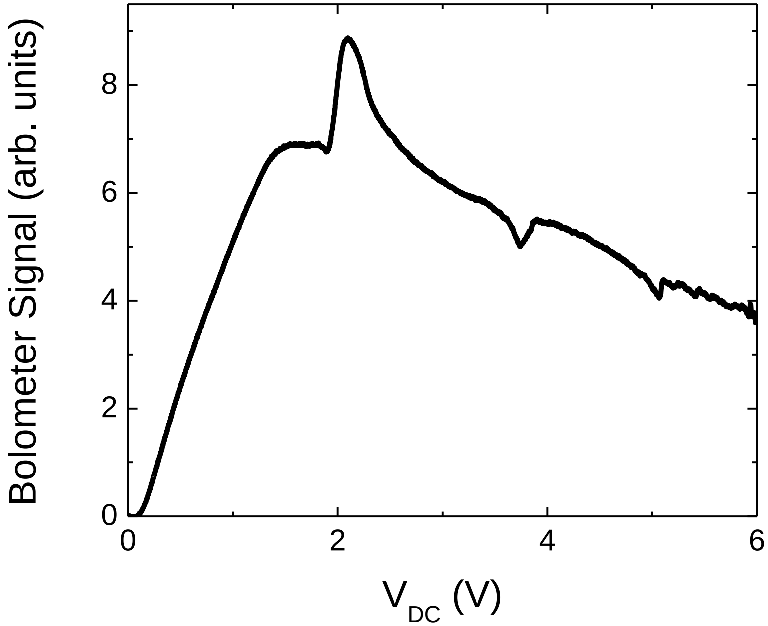
theoretical work on Bloch oscillations

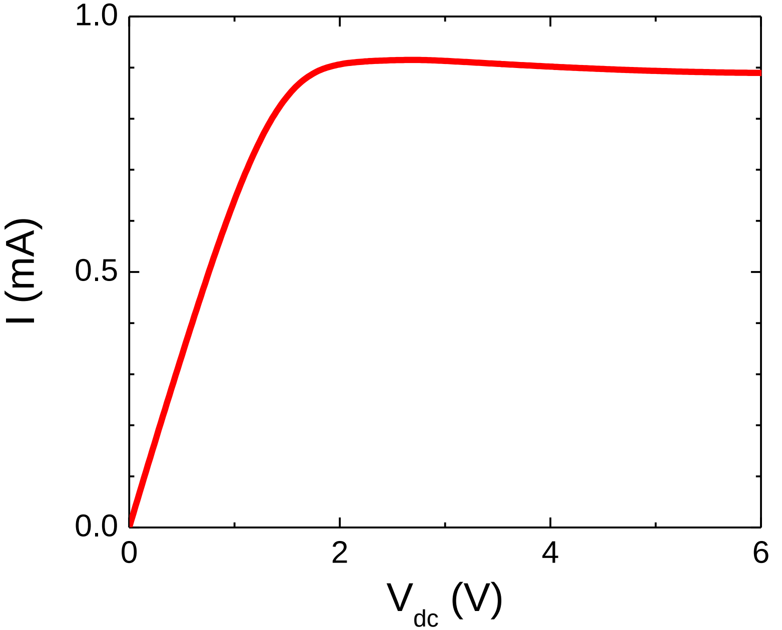
Ken Lyo

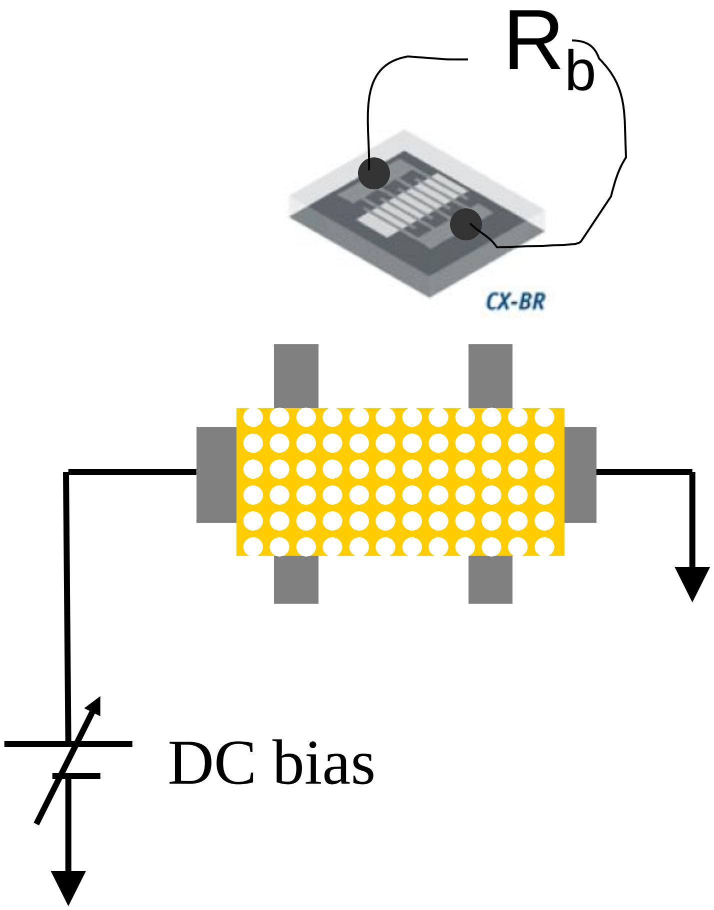


more results on Bloch oscillations

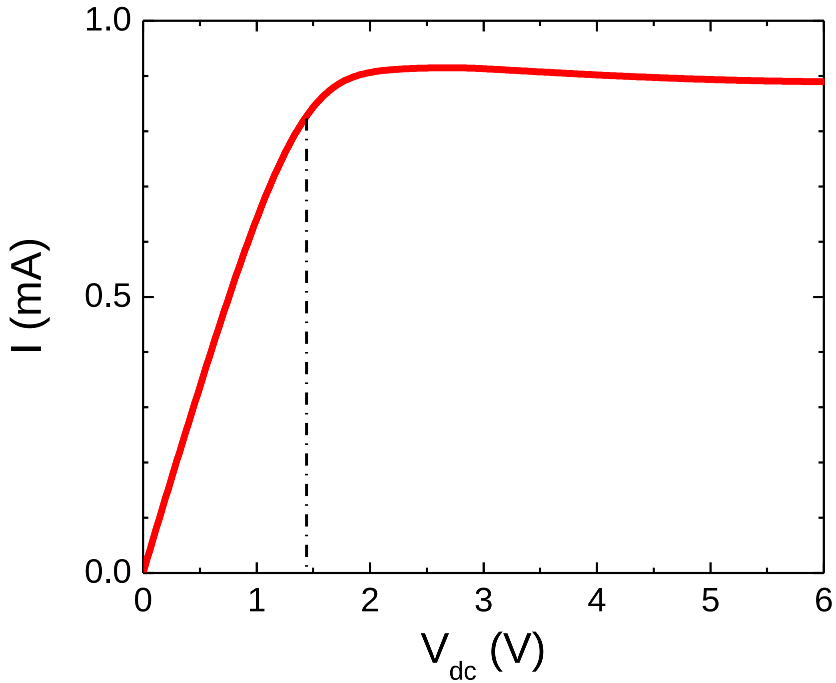
bolometric measurements

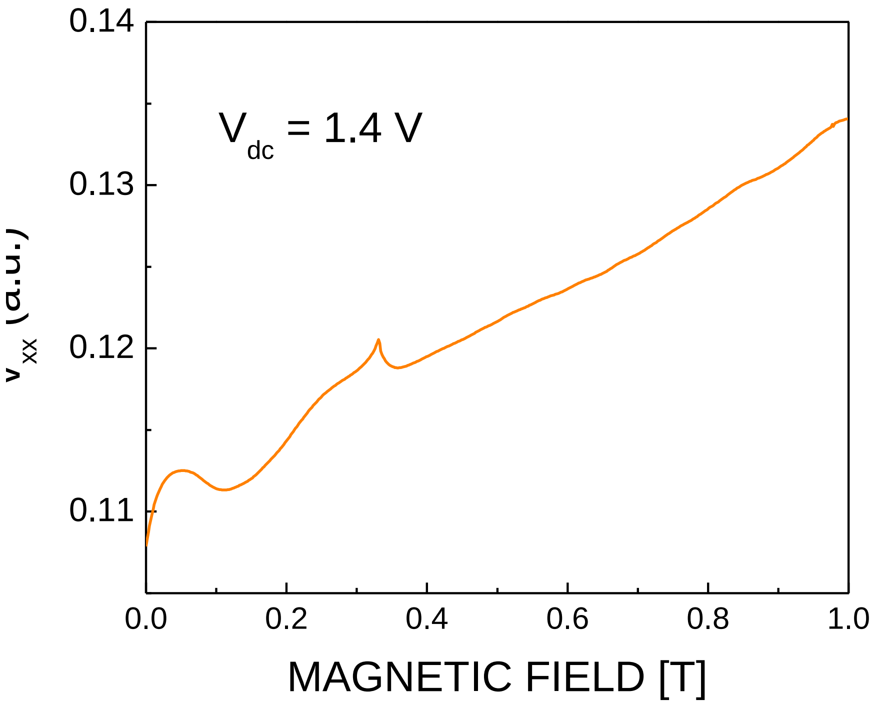


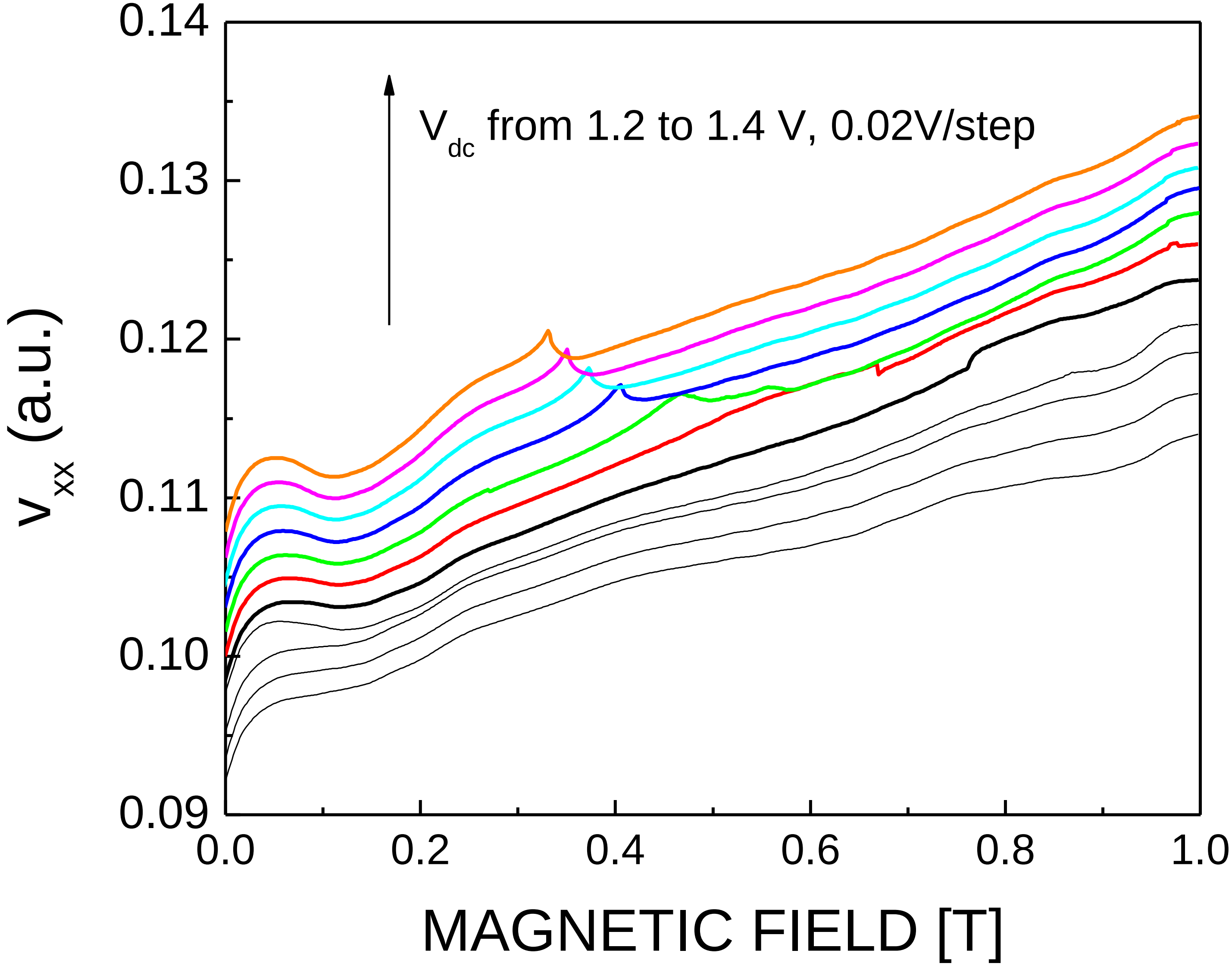




magneto transport at high electric fields

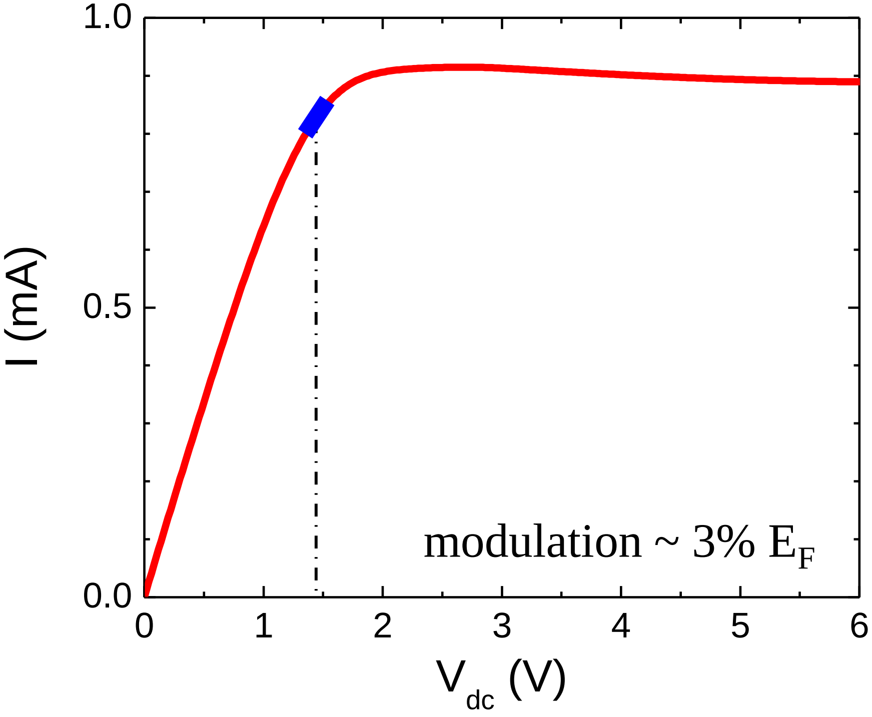


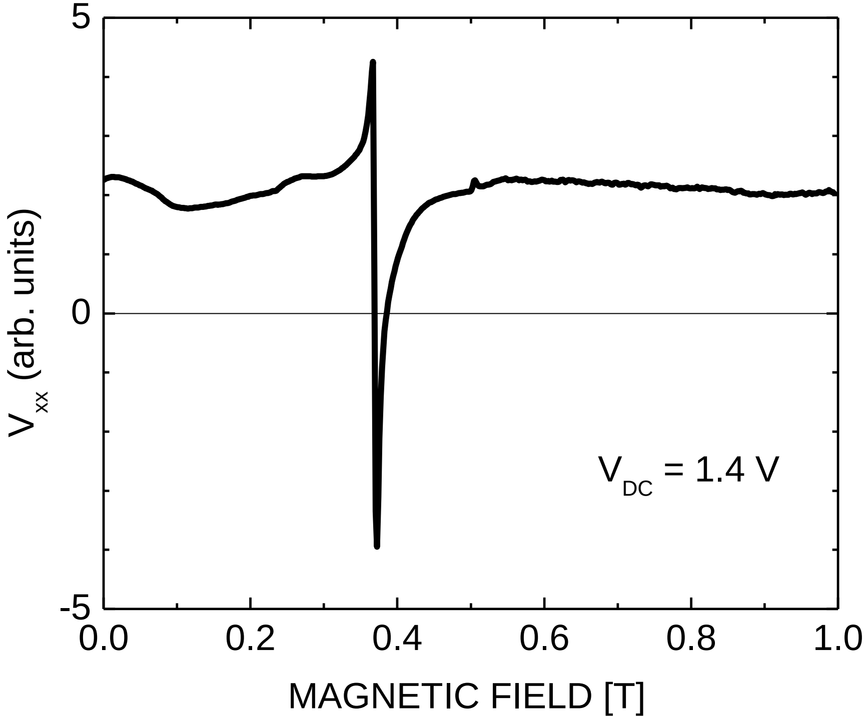


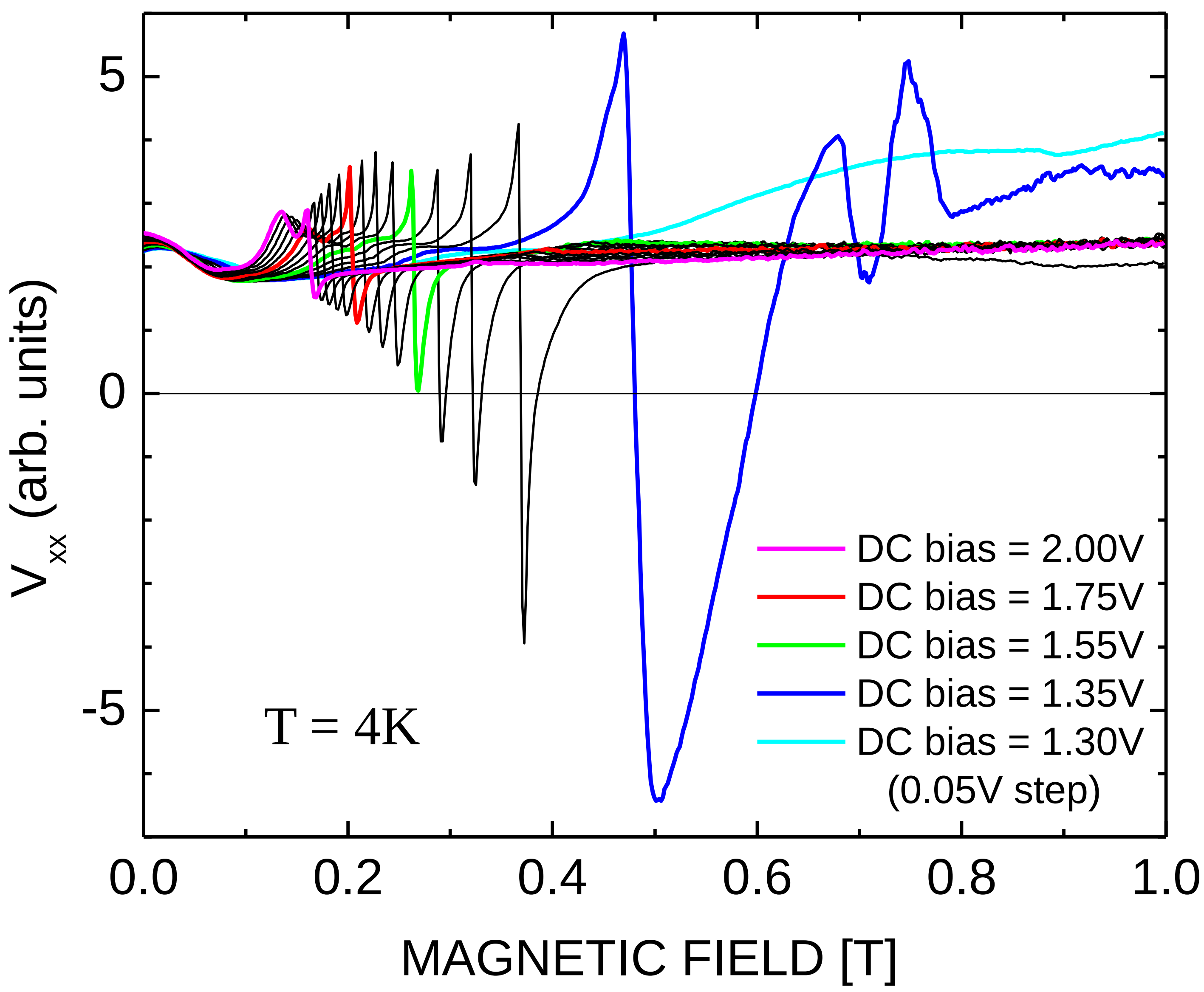


V$_{dc}$ from 1.2 to 1.4 V, 0.02V/step
0.14
0.13
0.12
0.11
0.10
0.09
v_{xx} (a.u.)
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]

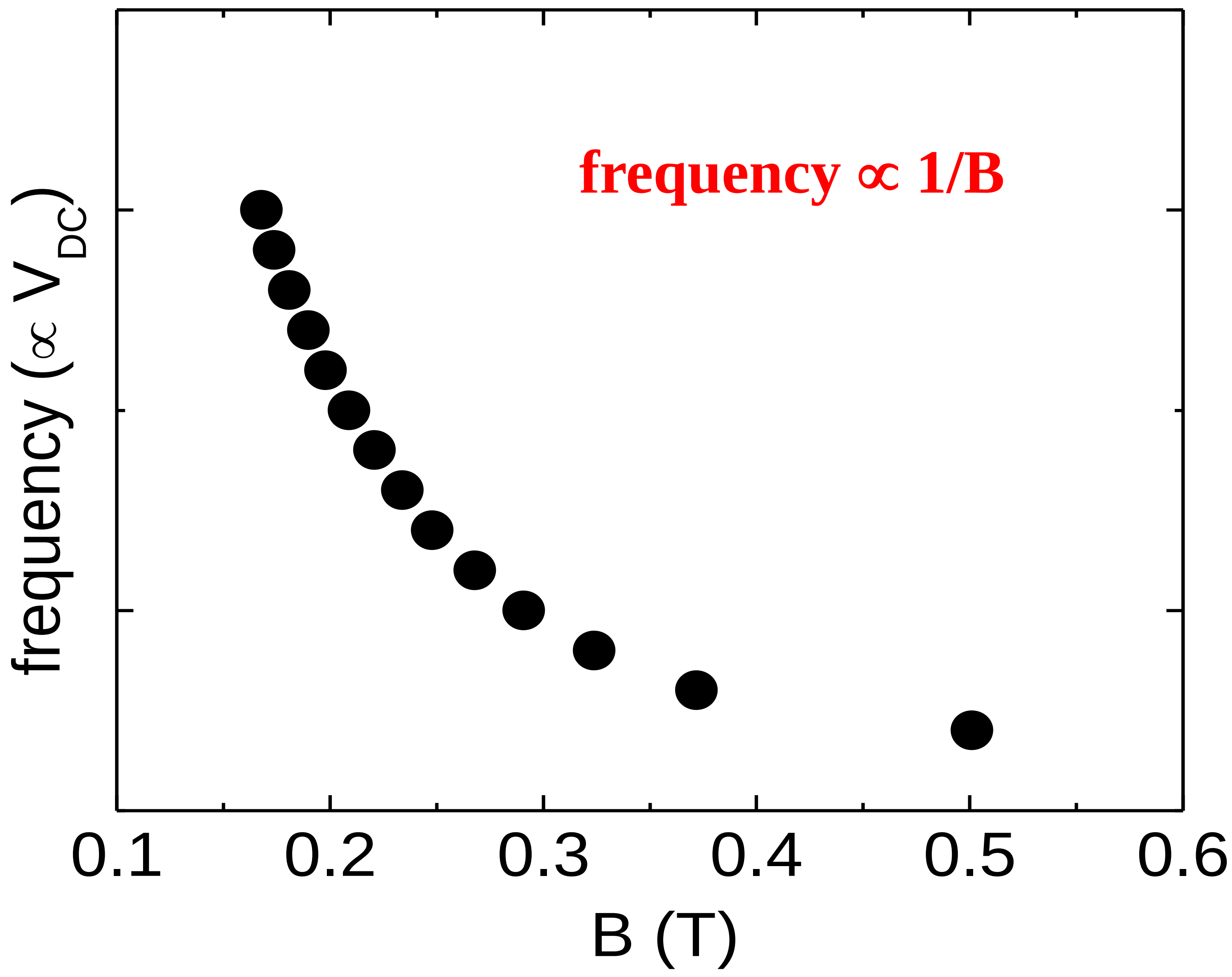
derivative measurement





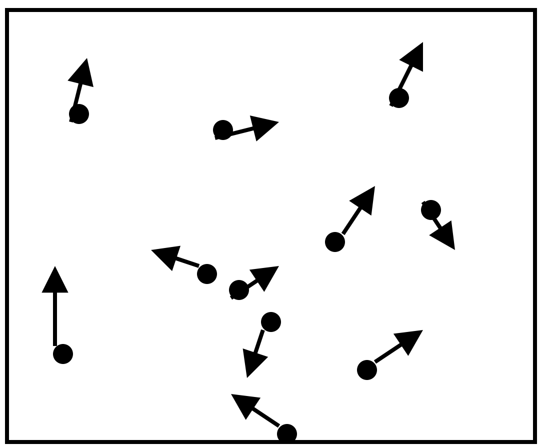


5
0
-5
V_{xx} (arb. units)
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]
T = 4K
DC bias = 2.00V
DC bias = 1.75V
DC bias = 1.55V
DC bias = 1.35V
DC bias = 1.30V
(0.05V step)

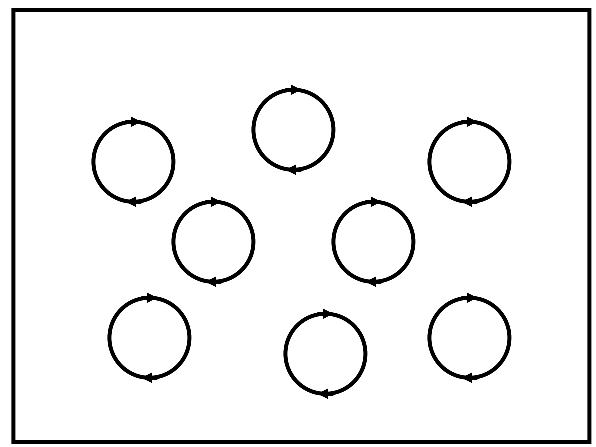

frequency ∝ 1/B
frequency (∝ V
DC
)
0.1
0.2
0.3
0.4
0.5
0.6
B (T)

Cyclotron motion

$B = 0$

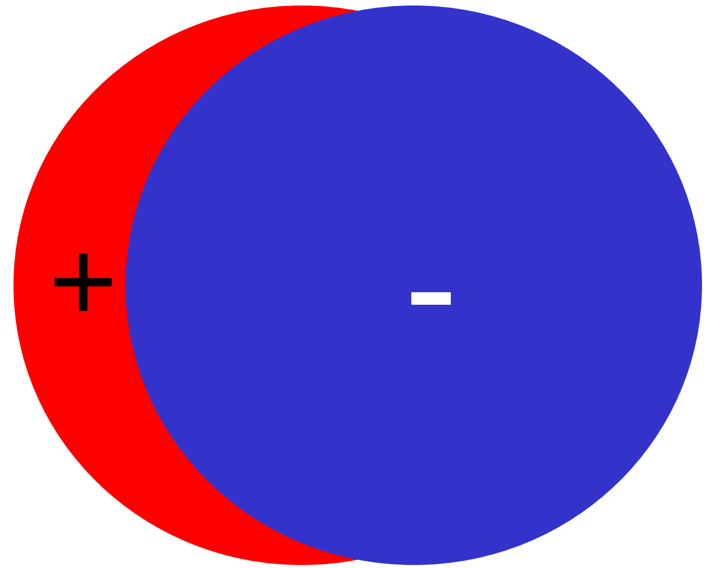


$B \neq 0$



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

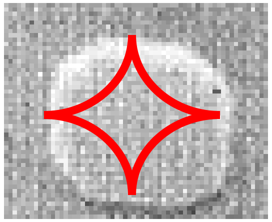
Plasmon oscillations



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

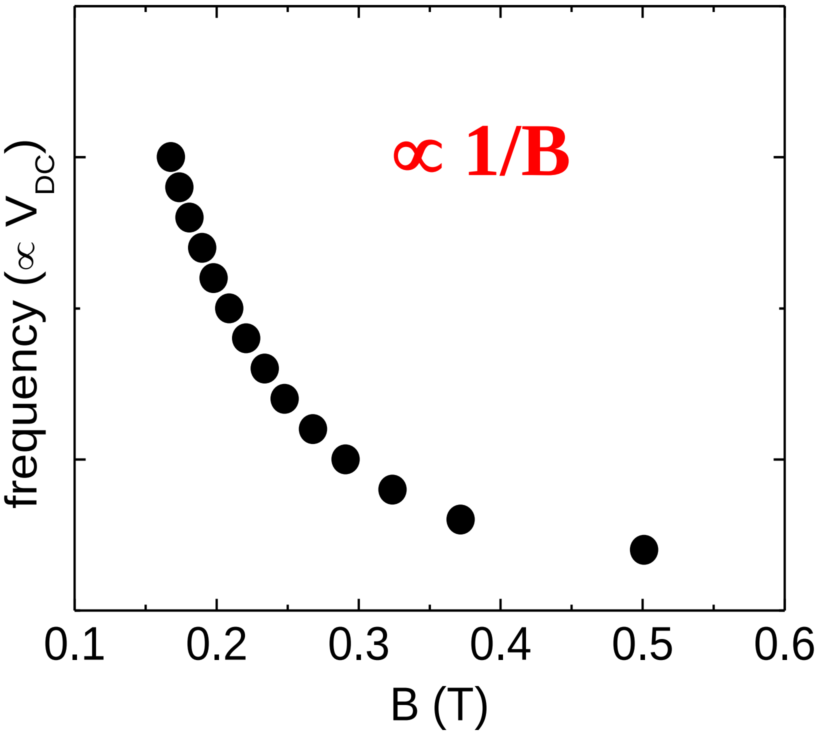
in an infinitely large sample, ω_0 is very small, no coupling between the cyclotron mode and plasmon mode.

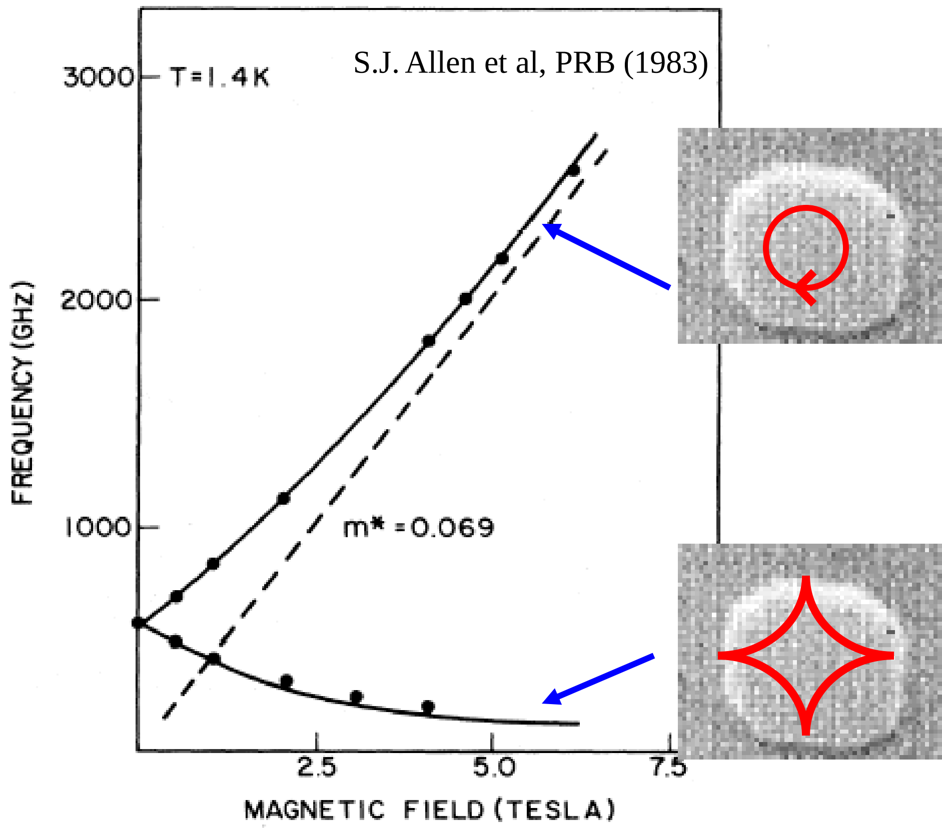
In a sample of finite size, ~ μm, there is strong coupling between the two. This results in a new resonance mode, edge magnetoplasmon mode.



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

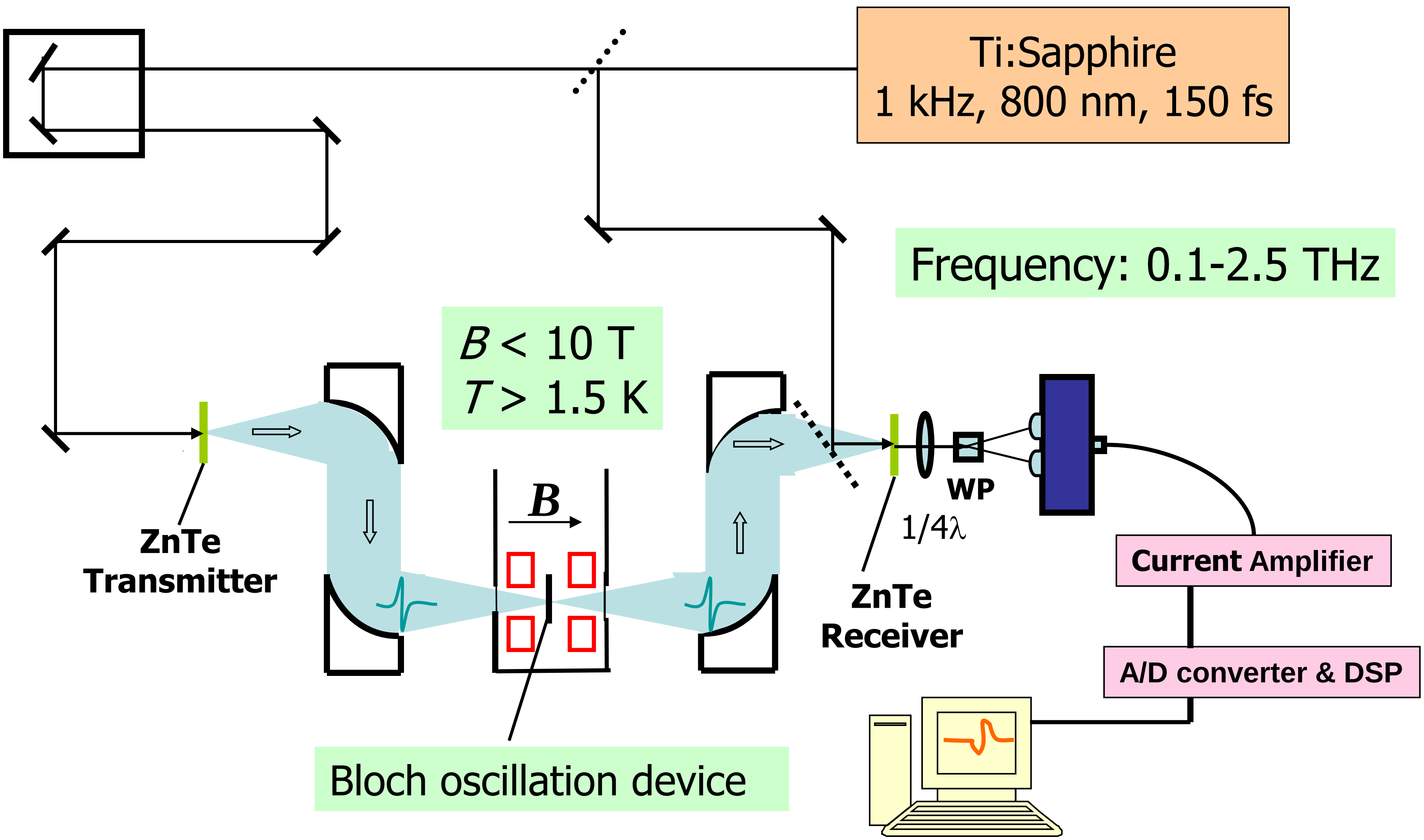
edge magnetoplasmon resonance





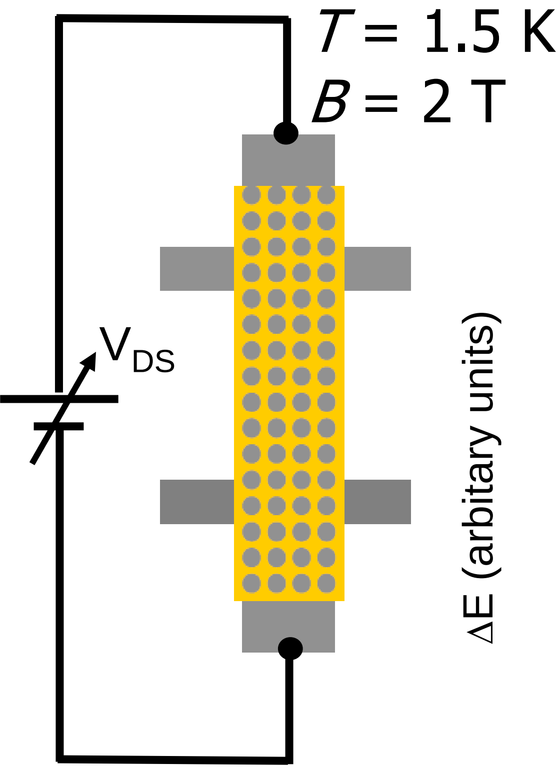
$\omega = -\omega_c/2 + [(\omega_c/2)^2 + \omega_0^2]^{1/2}$ $\propto$ **1/B** at high B fields

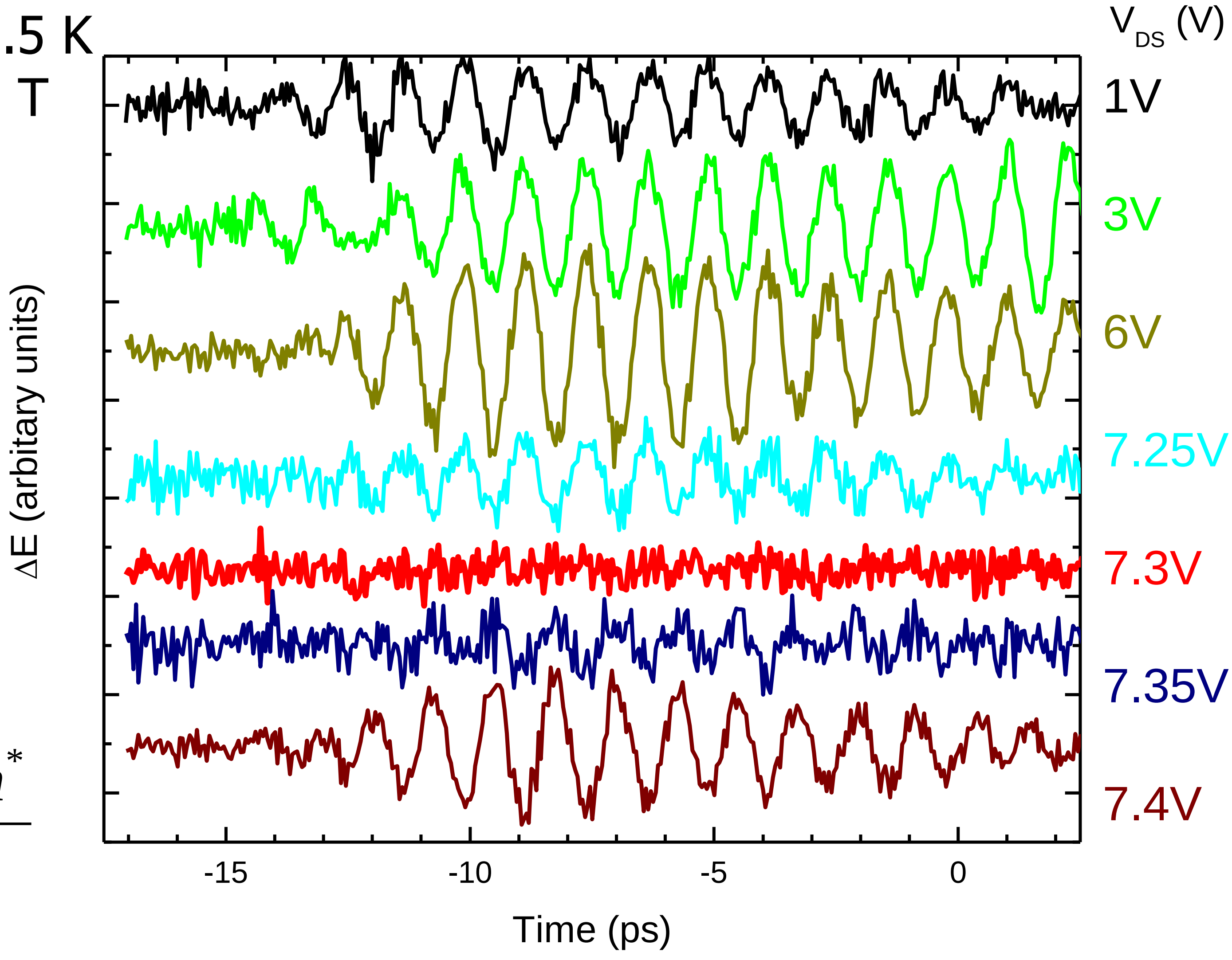
time-domain THz magneto-spectroscopy



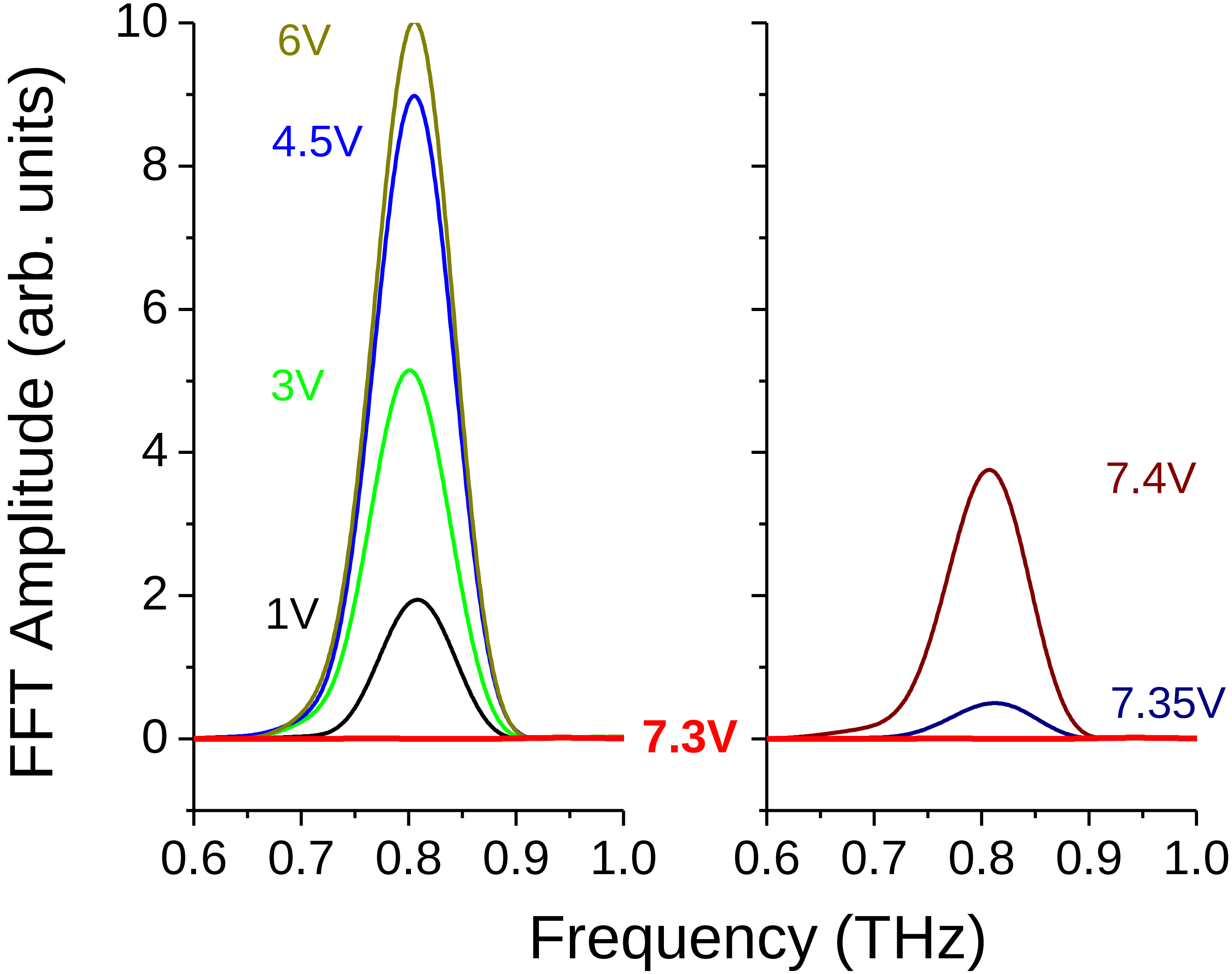
in collaboration with Jun Kono at Rice Univ.

coherent cyclotron resonance in Bloch oscillator



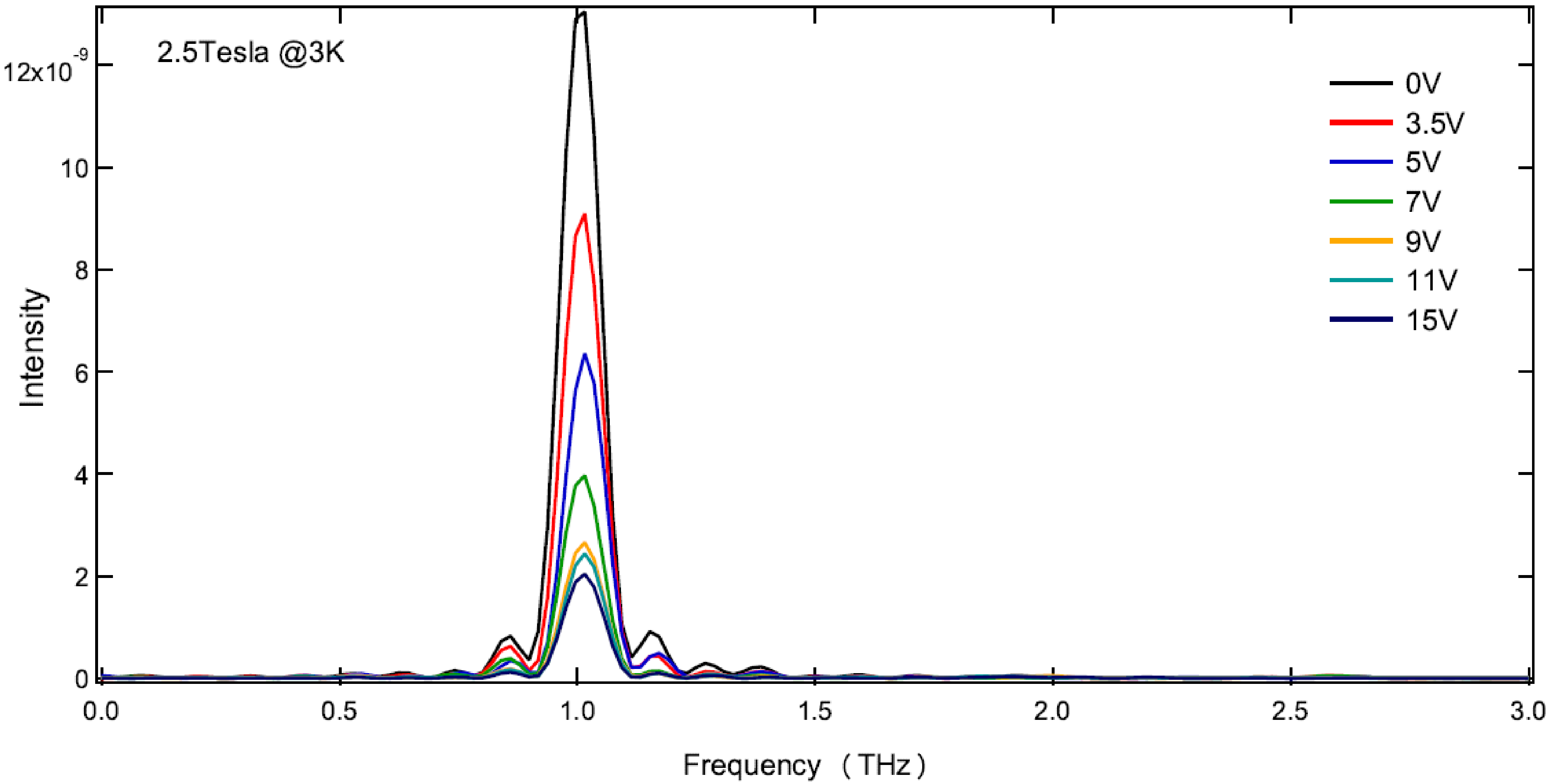


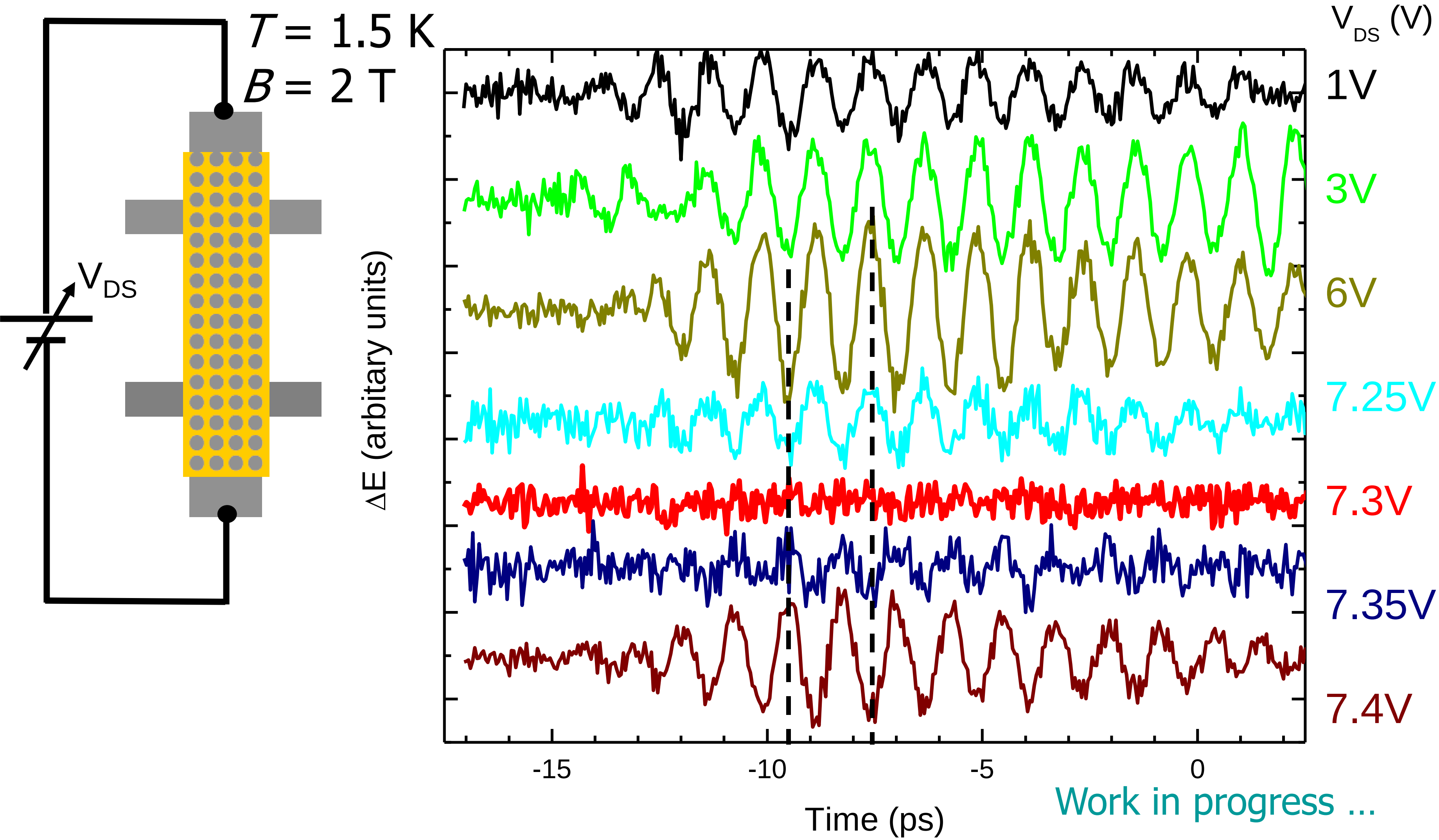
$$T_c = \frac{2\pi}{\omega_c} = \frac{2\pi m^*}{eB}$$



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

2D sample without patterning



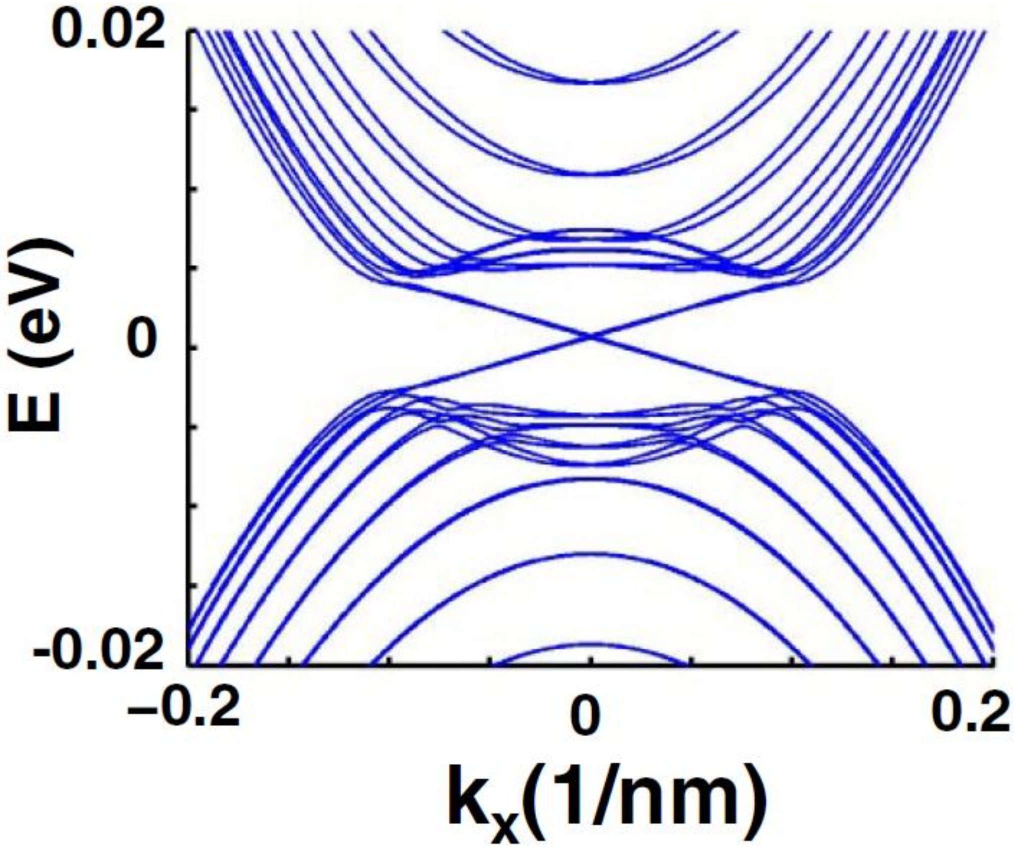


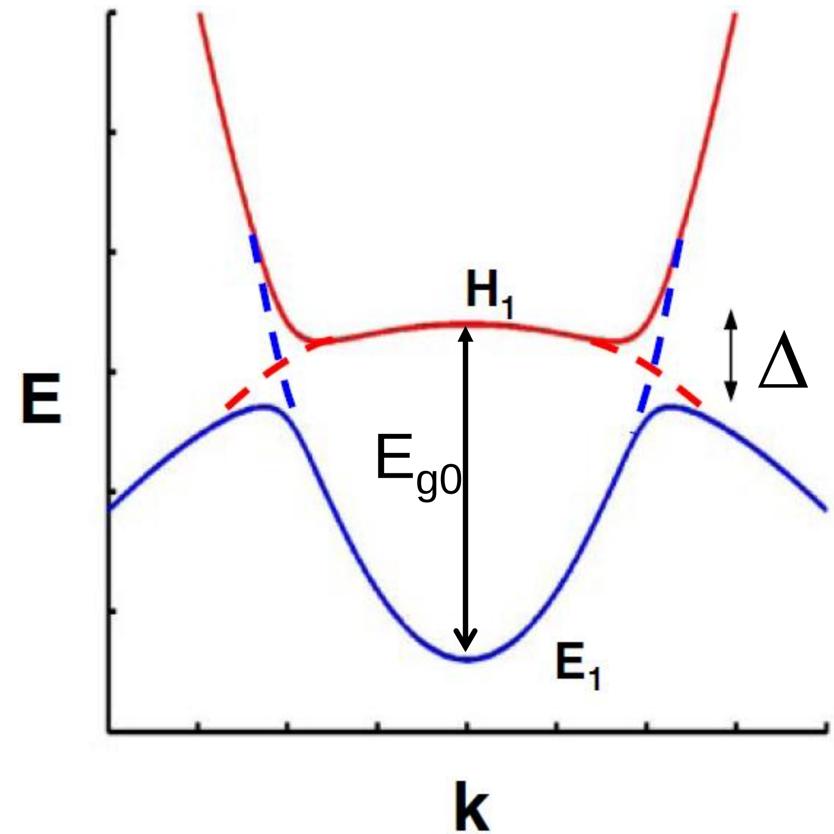
Work in progress ...

E-Field-Induced THz Phase Flip!

part II – anomalous circular conductivity law in two-dimensional topological insulator

The sample: InAs/GaSb type II heterostructure





Quantum spin Hall effect

C.X. Liu, T.L. Hughes, X.L. Qi, K. Wang, and S.C. Zhang, Phys. Rev. Lett. **100**, 236601 (2008).

Growth structure:

air

InAs 20A (or GaSb 20A)

AlSb 500A

GaSb QW 50A

InAs QW 150A

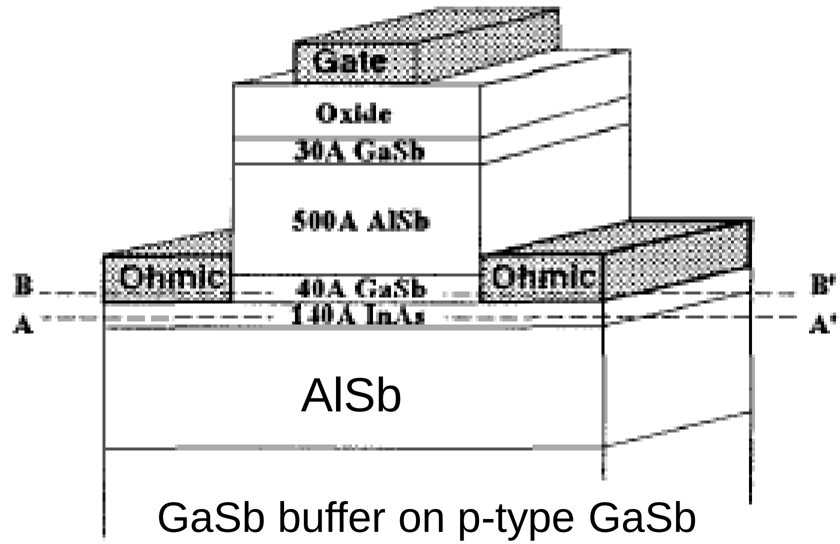
AlSb 1um

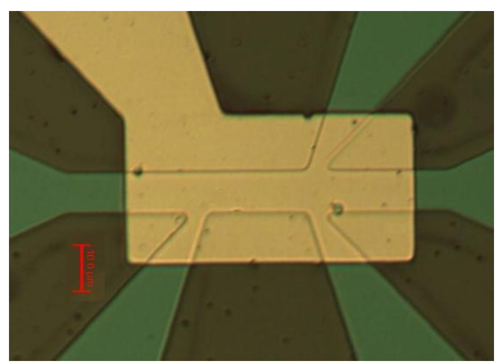
GaSb 1um

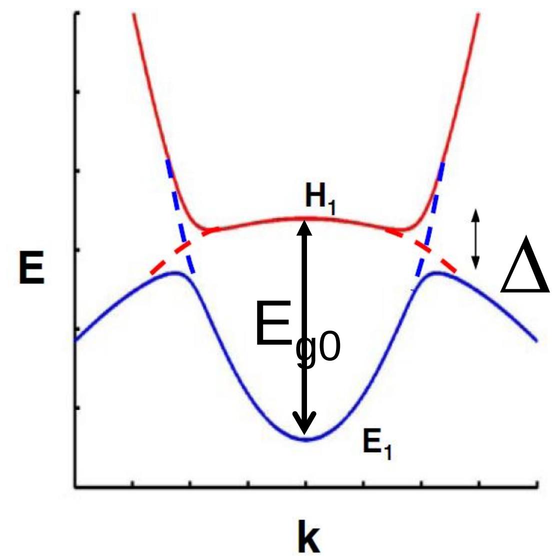
GaSb substrate (p-doped)

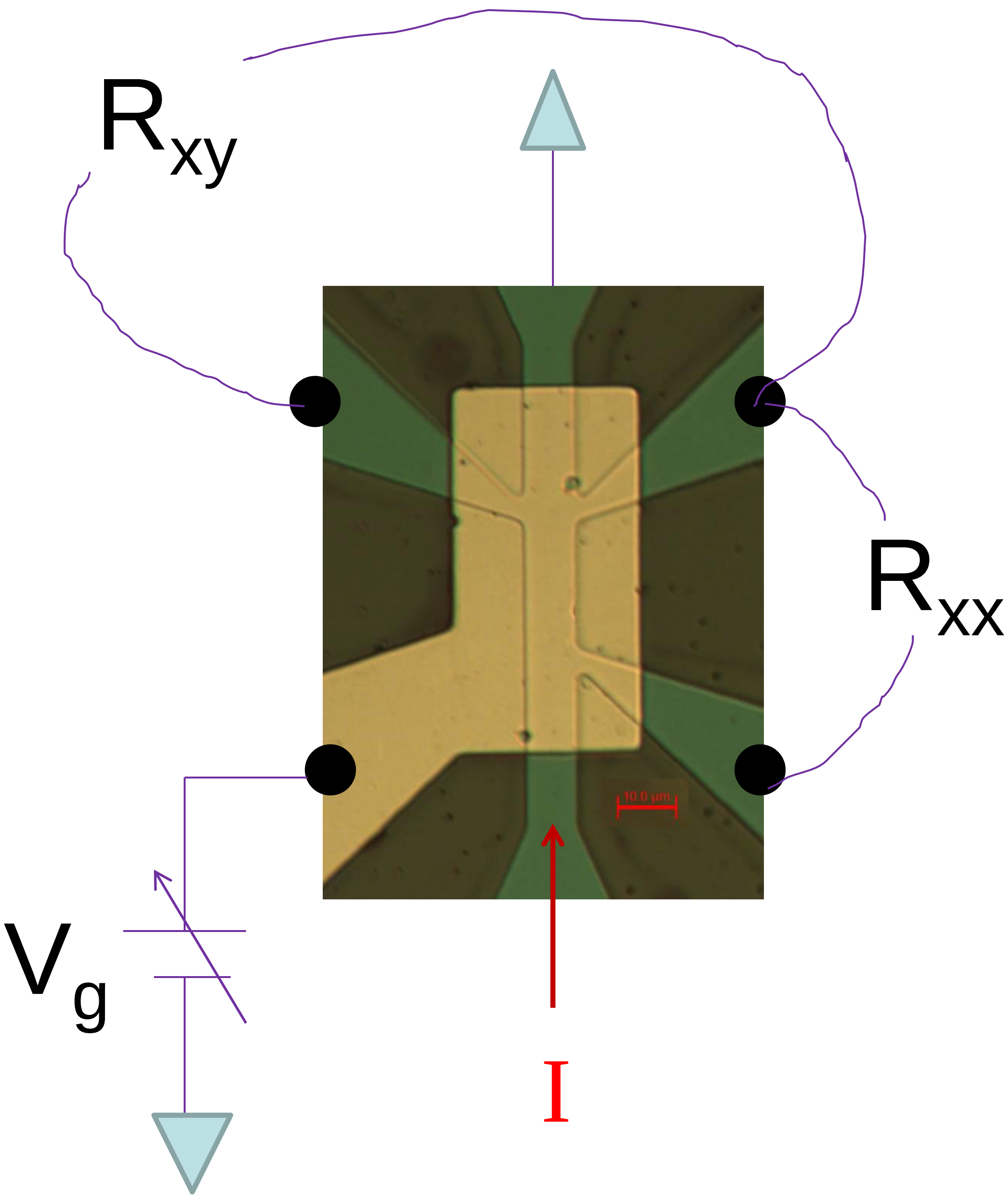
Field-effect transistor:

Yang et al, Appl. Phys. Lett. **69**, 85 (1996).





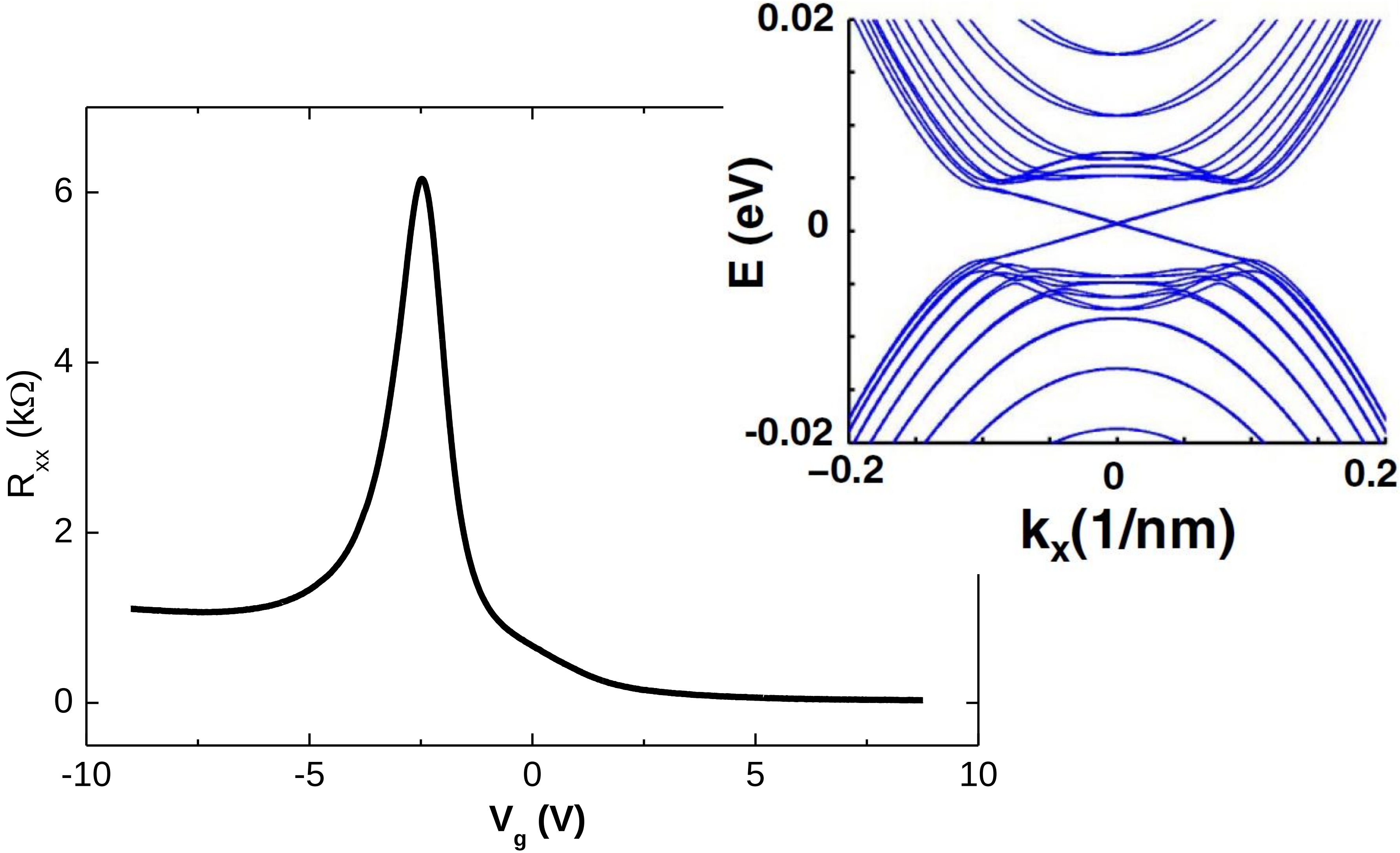




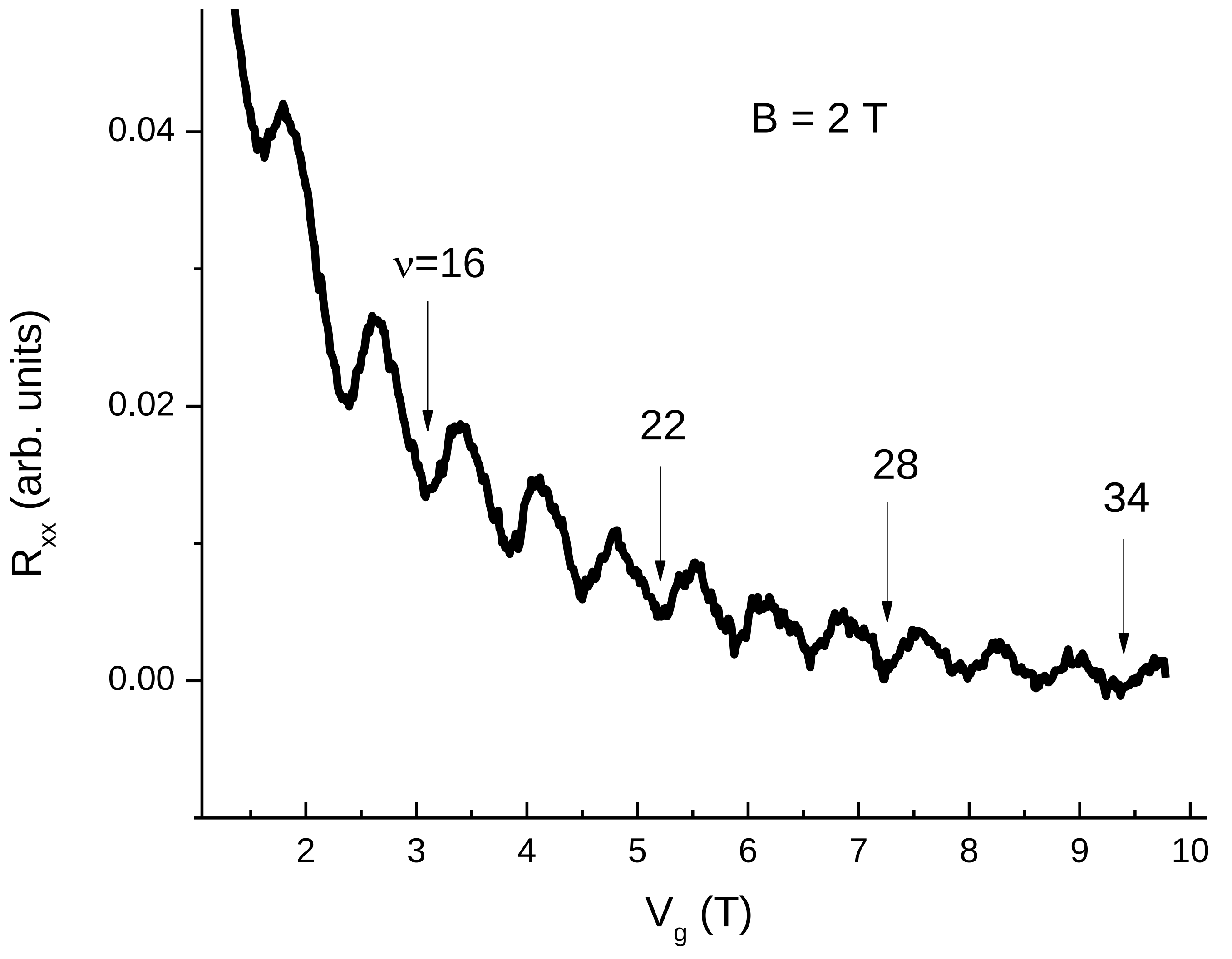
$$\sigma_{xx} = R_{xx}/(R_{xx}^2+R_{xy}^2)$$

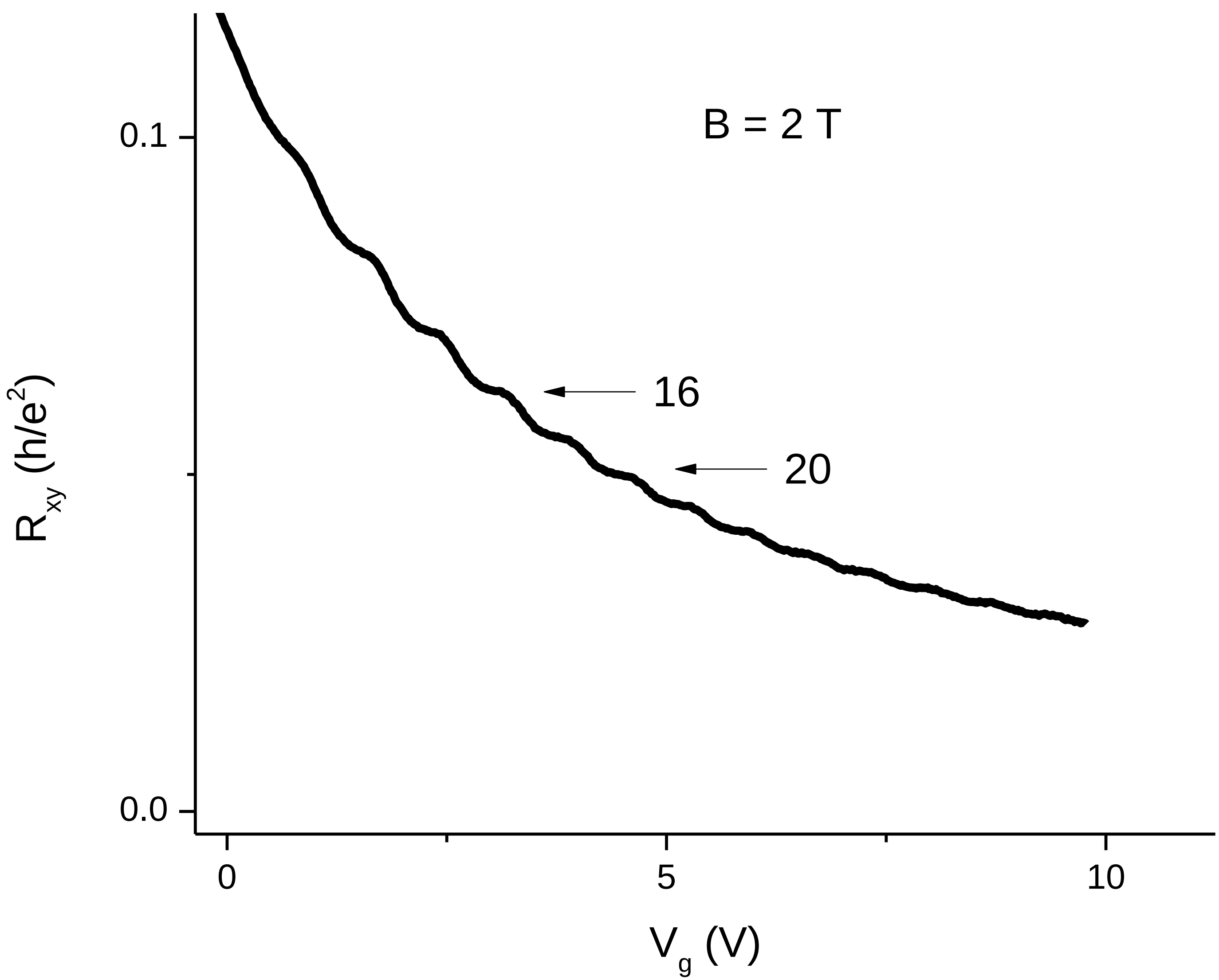
$$\sigma_{xy} = R_{xx}/(R_{xx}^2+R_{xy}^2)$$

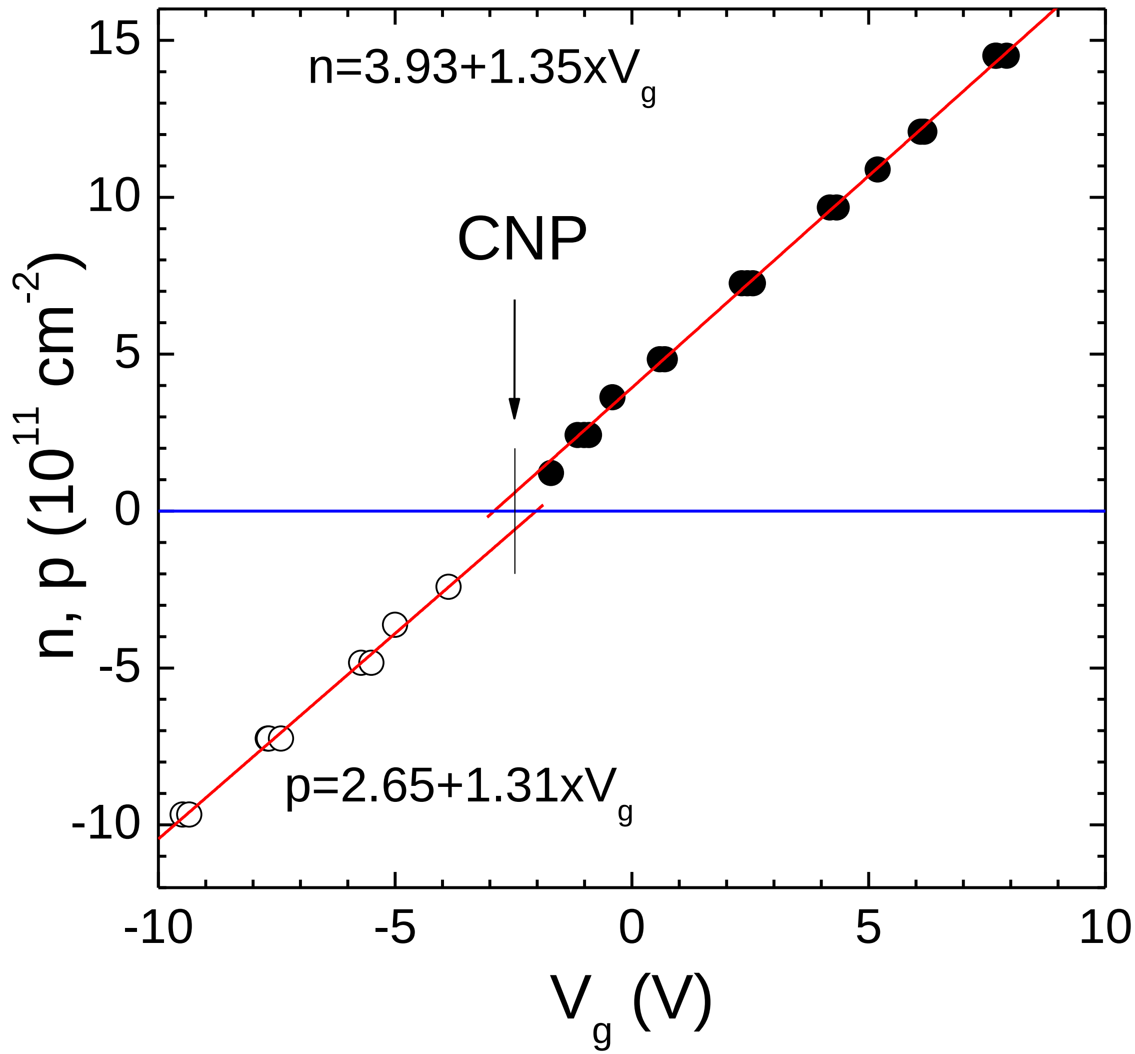
Electron transport at zero magnetic field:



Electron transport at low magnetic fields:

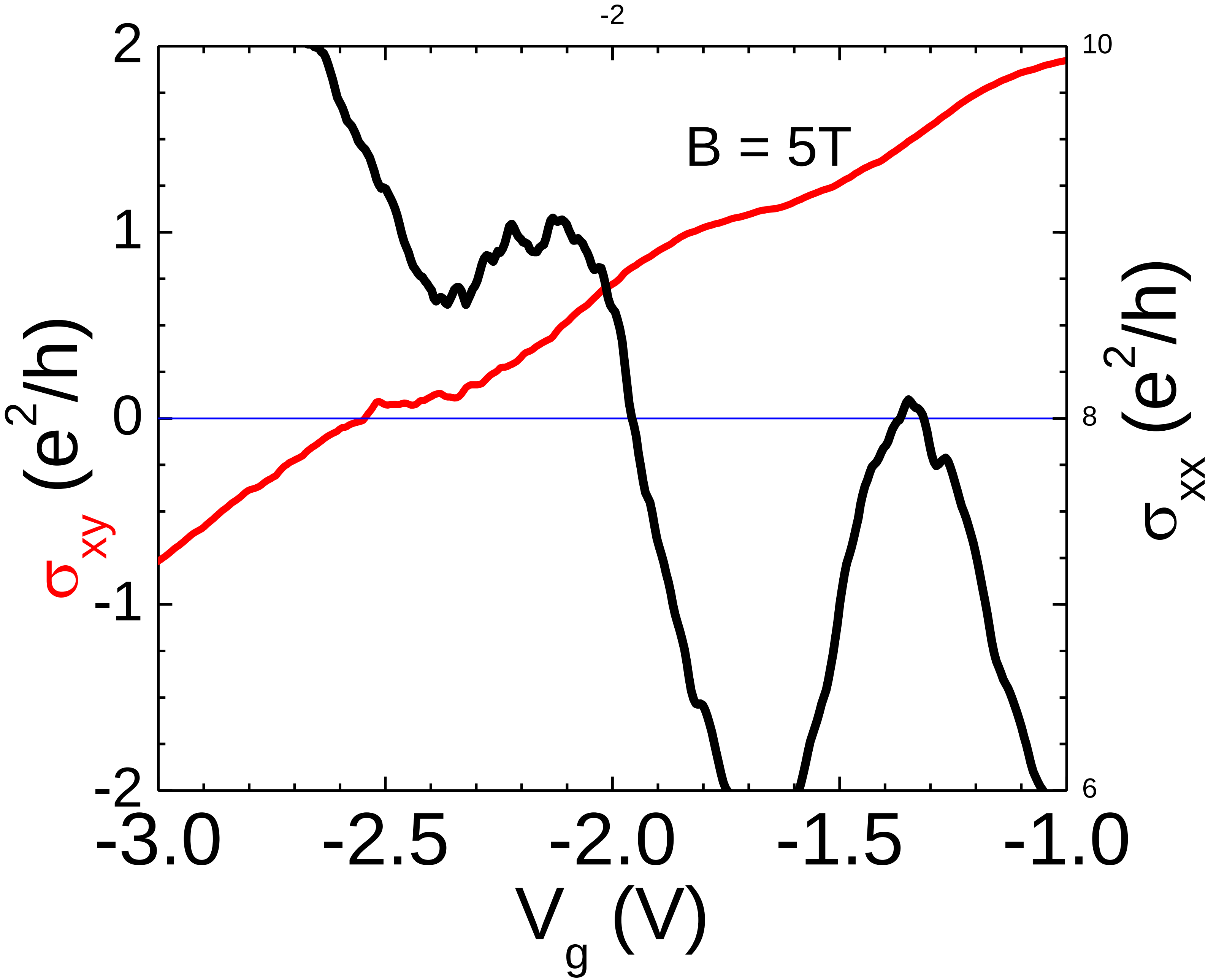



B = 2 T
16
20
0.1
0.0
0
5
10
R_{xy} (h/e^2)
V_g (V)

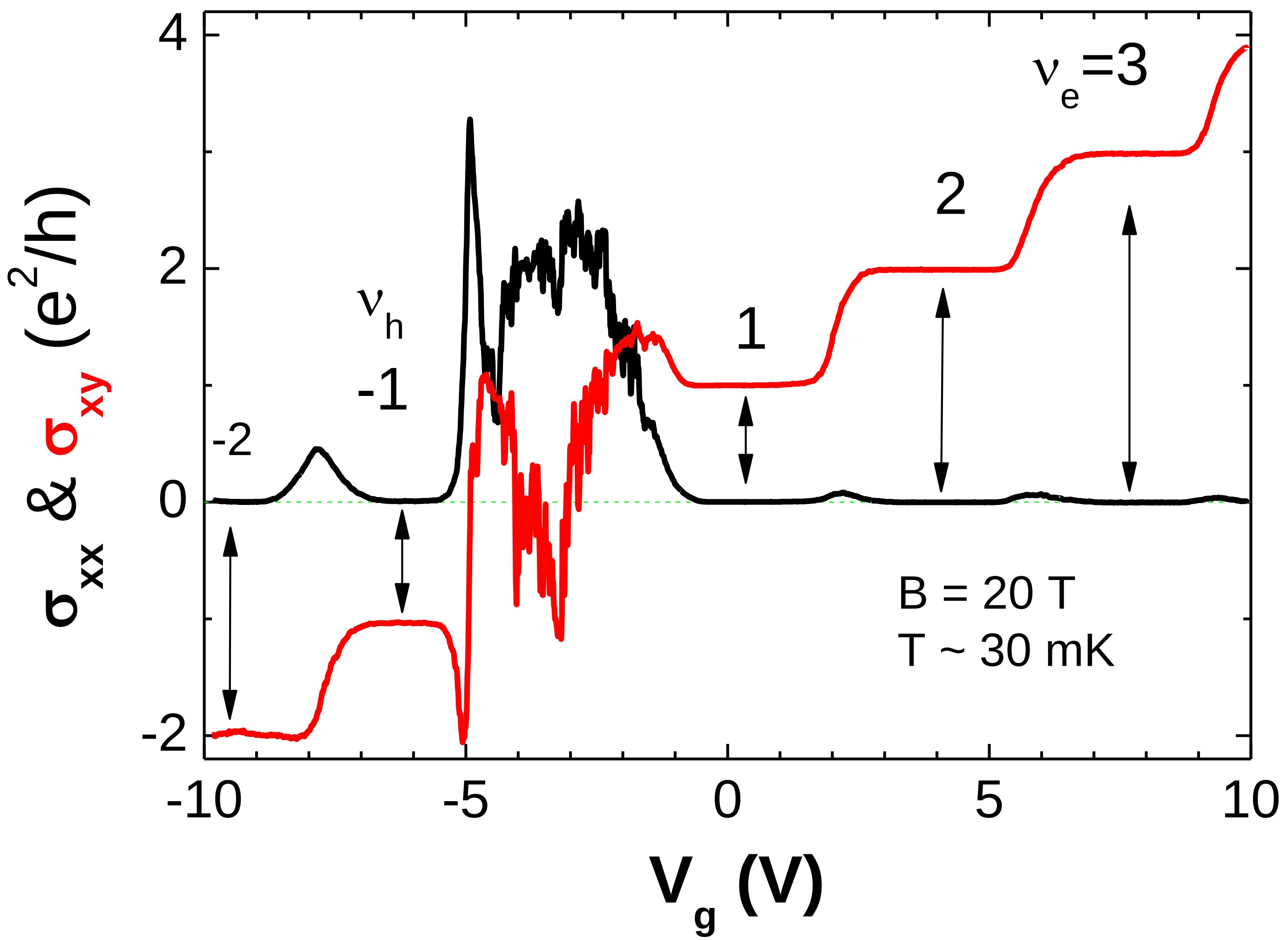


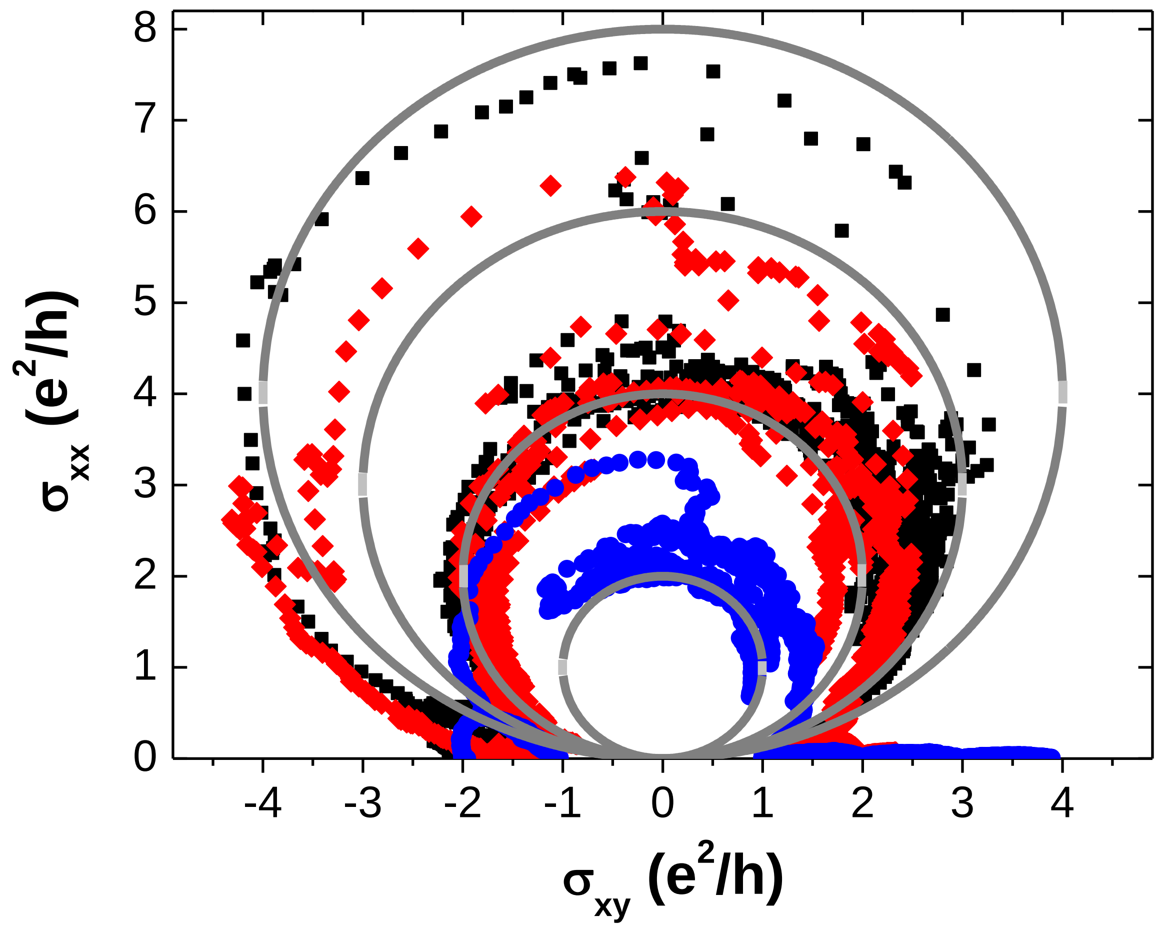
At CNP $(n + p = 0)$

$|n| = |p| \sim 0.6 \times 10^{11}\ cm^{-2}$


-2
2
1
0
-1
-2
10
8
6
B = 5T
σ_{xy} (e^2/h)
σ_{xx} (e^2/h)
-3.0
-2.5
-2.0
-1.5
-1.0
V_g (V)

Electron transport at high magnetic fields:





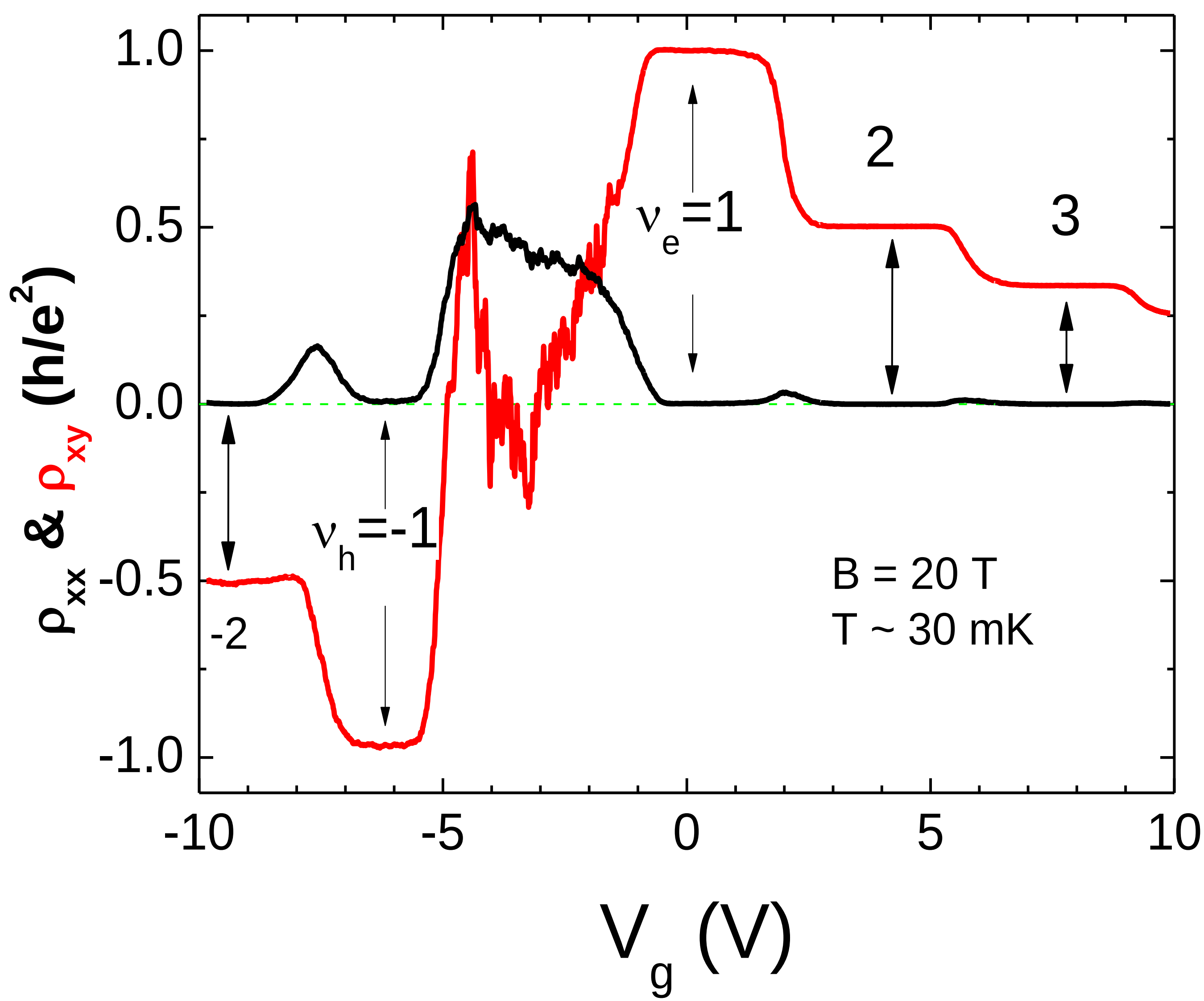
$$(\sigma_{xx} - N)^2 + \sigma_{xy}{}^2 = N^2$$

N= 1, 2, 3, …

$$(\sigma_{xx} - N)^2 + \sigma_{xy}^2 = N^2$$

$$\Downarrow$$

$$\rho_{xx} = h/e^2/(2N)$$



1.0
0.5
0.0
-0.5
-1.0
-10
-5
0
5
10
ρ_{xx} & ρ_{xy} (h/e^2)
V_g (V)
ν_e=1
2
3
ν_h=-1
-2
B = 20 T
T ~ 30 mK

$$(\sigma_{xx} - N)^2 + \sigma_{xy}{}^2 = N^2$$

$$\rho_{xx} = h/e^2/(2N)$$

Due to quantum spin Hall effect?

C.X. Liu, T.L. Hughes, X.L. Qi, K. Wang, and S.C. Zhang, Phys. Rev. Lett. **100**, 236601 (2008).
I. Knez, R.R. Du, and G. Sullivan, Phys. Rev. Lett. **107**, 136603 (2011).

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Thank you!