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Revisiting old issues in two dimensional electron systems

Wei Pan
Sandia National Labs

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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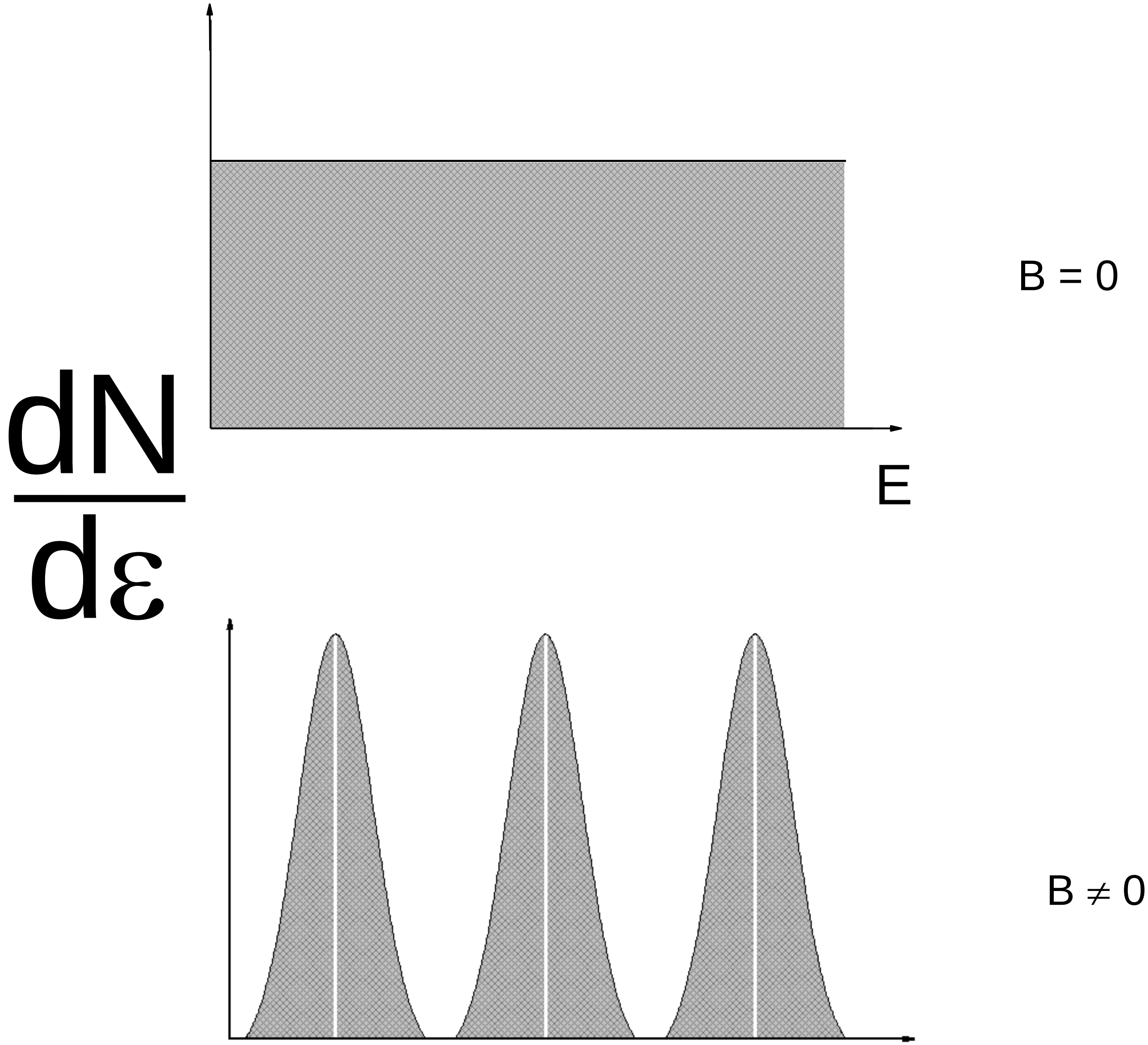
- **Observation of anti-levitation of Landau levels in vanishing magnetic fields**

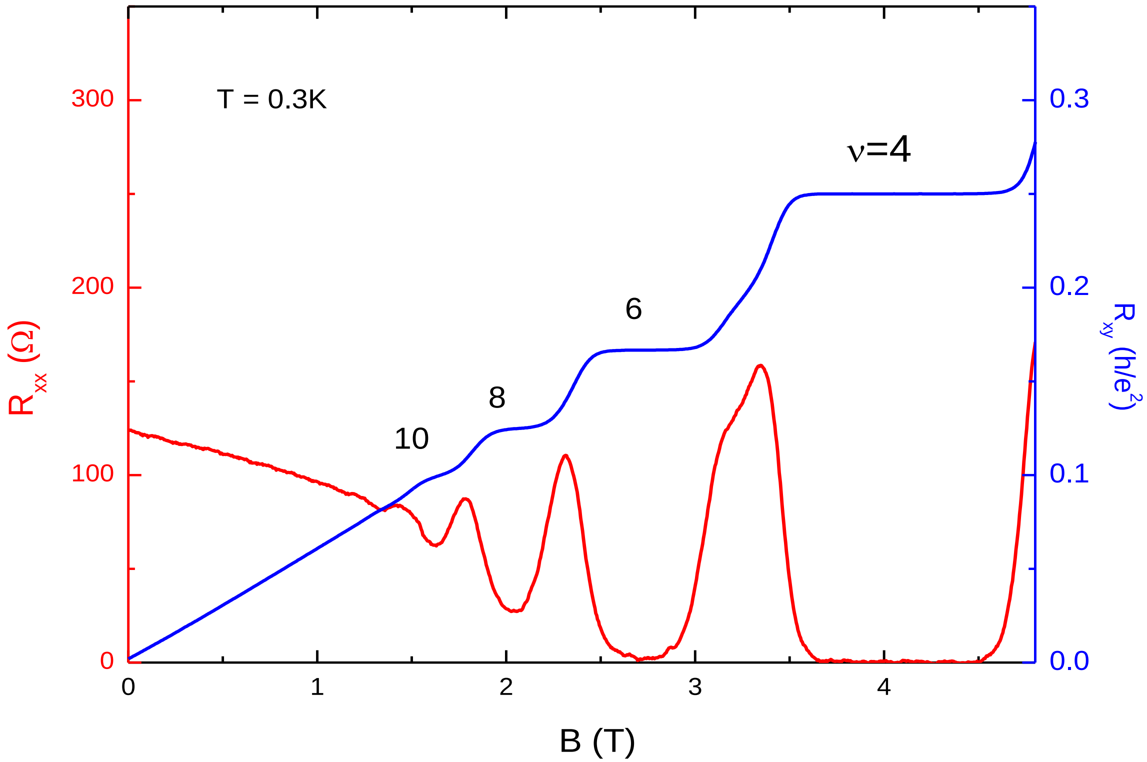
- **Bloch oscillations in 2D superlattices**

outline

- Background
- Sample
  - HIGFET (**H**eterojunction **I**nsulated-**G**ate **F**ield-**E**ffect **T**ransistor)
    - High quality 2DEG, peak mobility $\mu \sim 10^7$ cm^2/Vs at $n \sim 1.5\times10^{11}$ cm^{-2}.
- Result
  - Anti-levitation is observed at low Landau level fillings ν=4,5,6.
  - No (anti) levitation at high Landau level fillings
  - This observation is in good agreement with recent theoretical predictions (C. Wang et al, PRB **89**, 045314 (2014)).


B = 0
$\frac{dN}{d\varepsilon}$
E
B ≠ 0

Integer quantum Hall effect (IQHE)



R_{xy} quantized

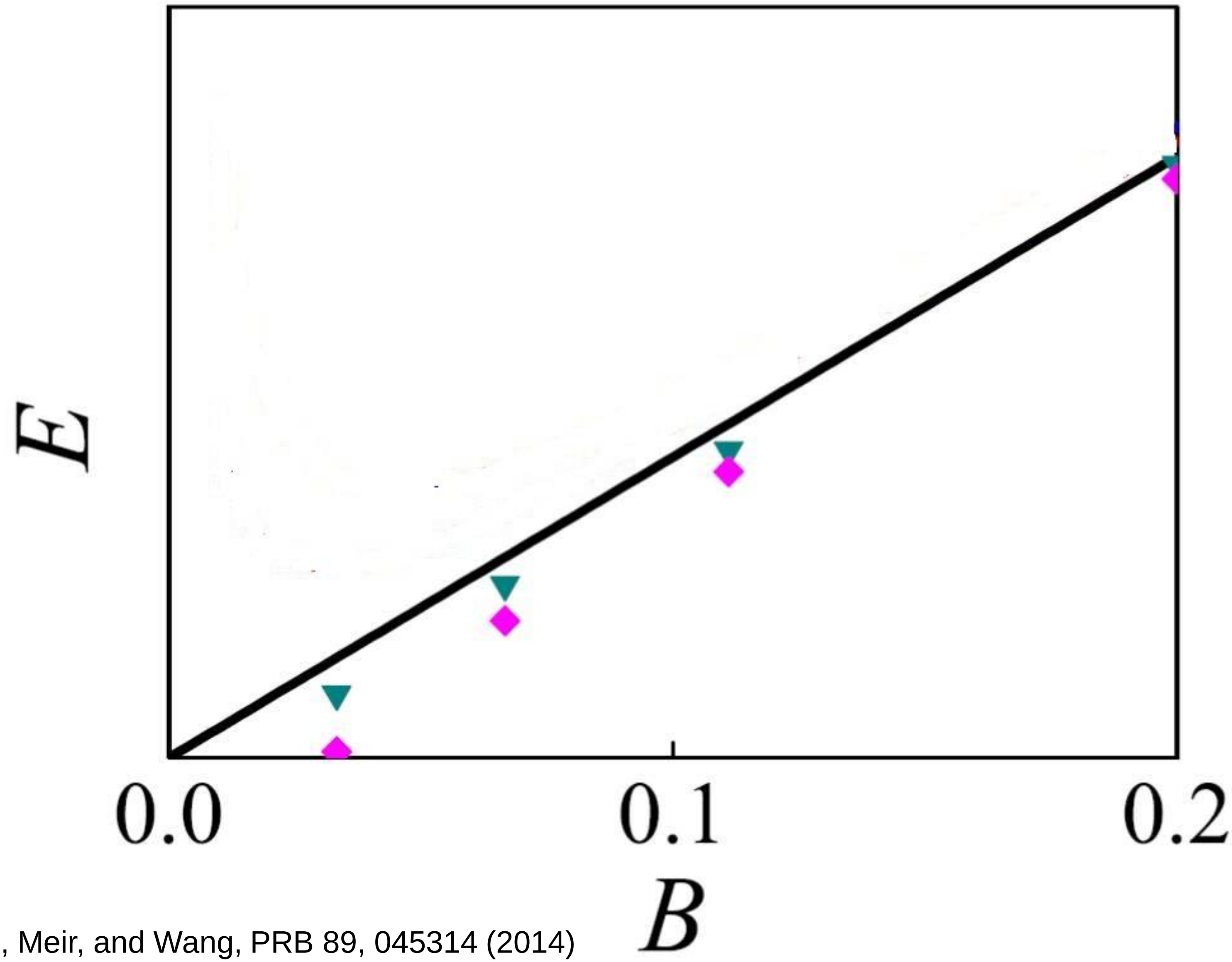
$$R_{xy} = \frac{h}{\nu e^2}$$

R_{xx} zero

ν – Landau level filling

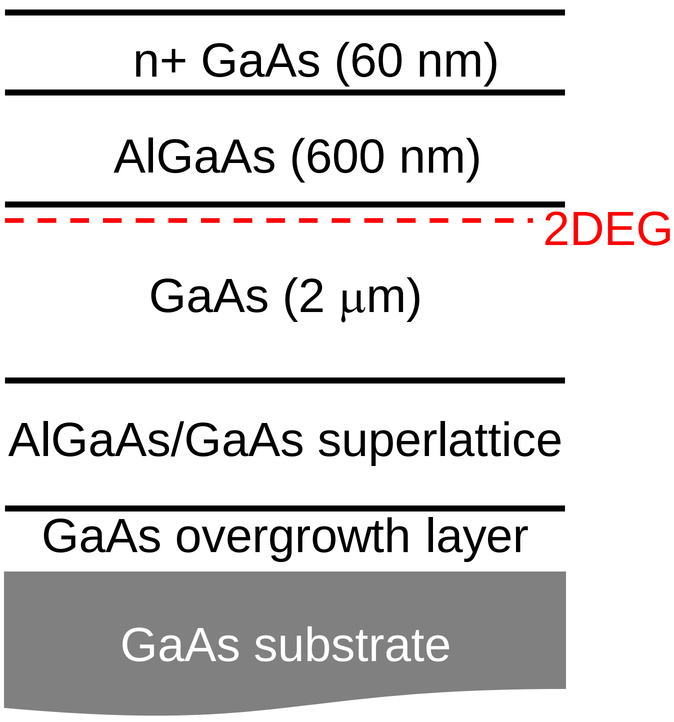
ν = nh/eB (n density)

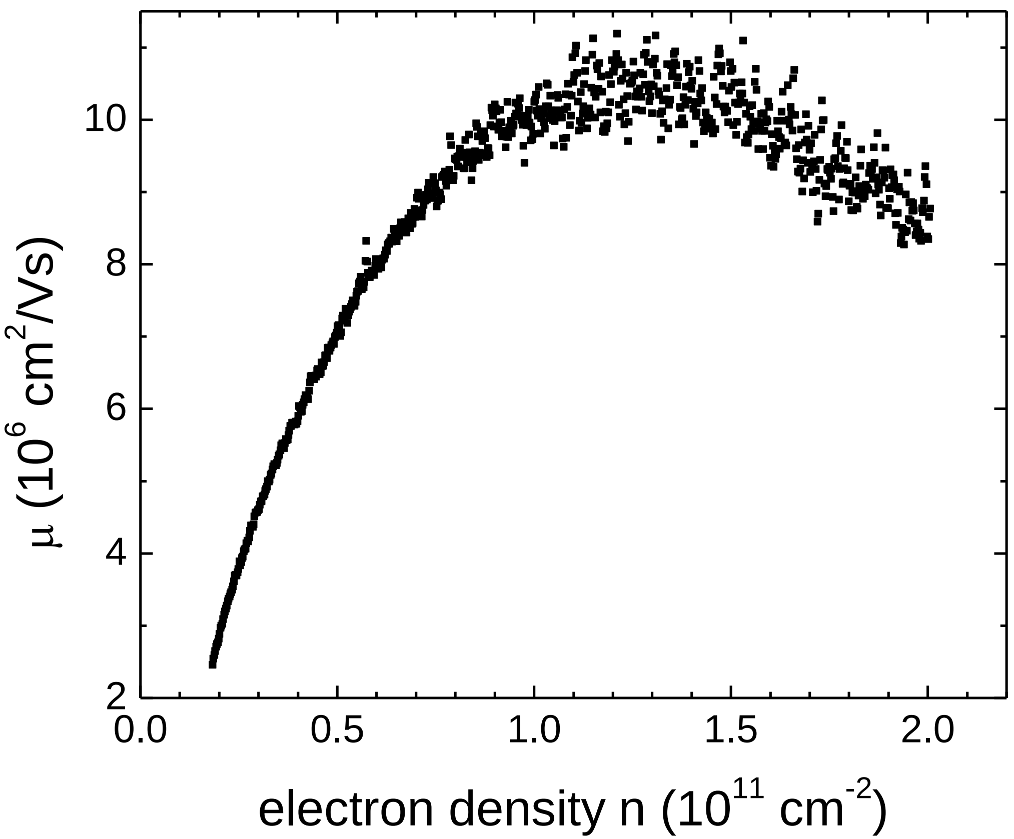
Floating or anti-floating of Landau levels in vanishing B field?



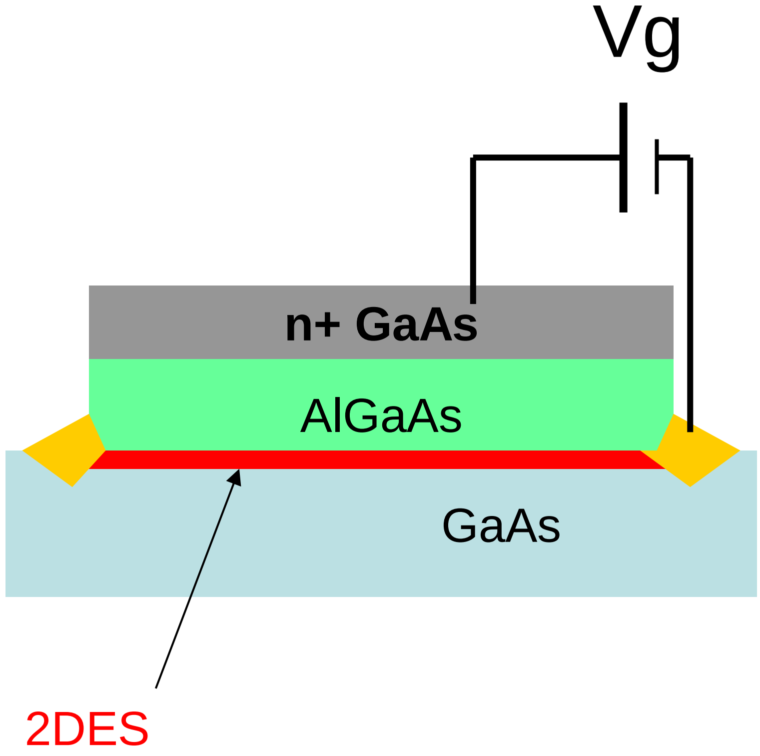
Wang, Avishai, Meir, and Wang, PRB 89, 045314 (2014)

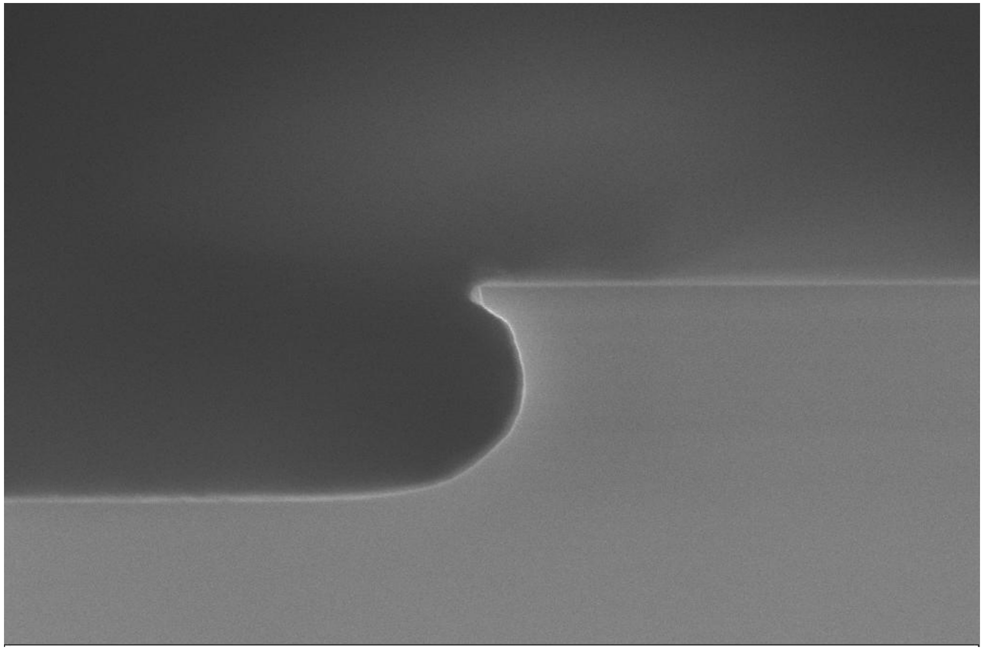
HIGFET
high mobility down to low densities

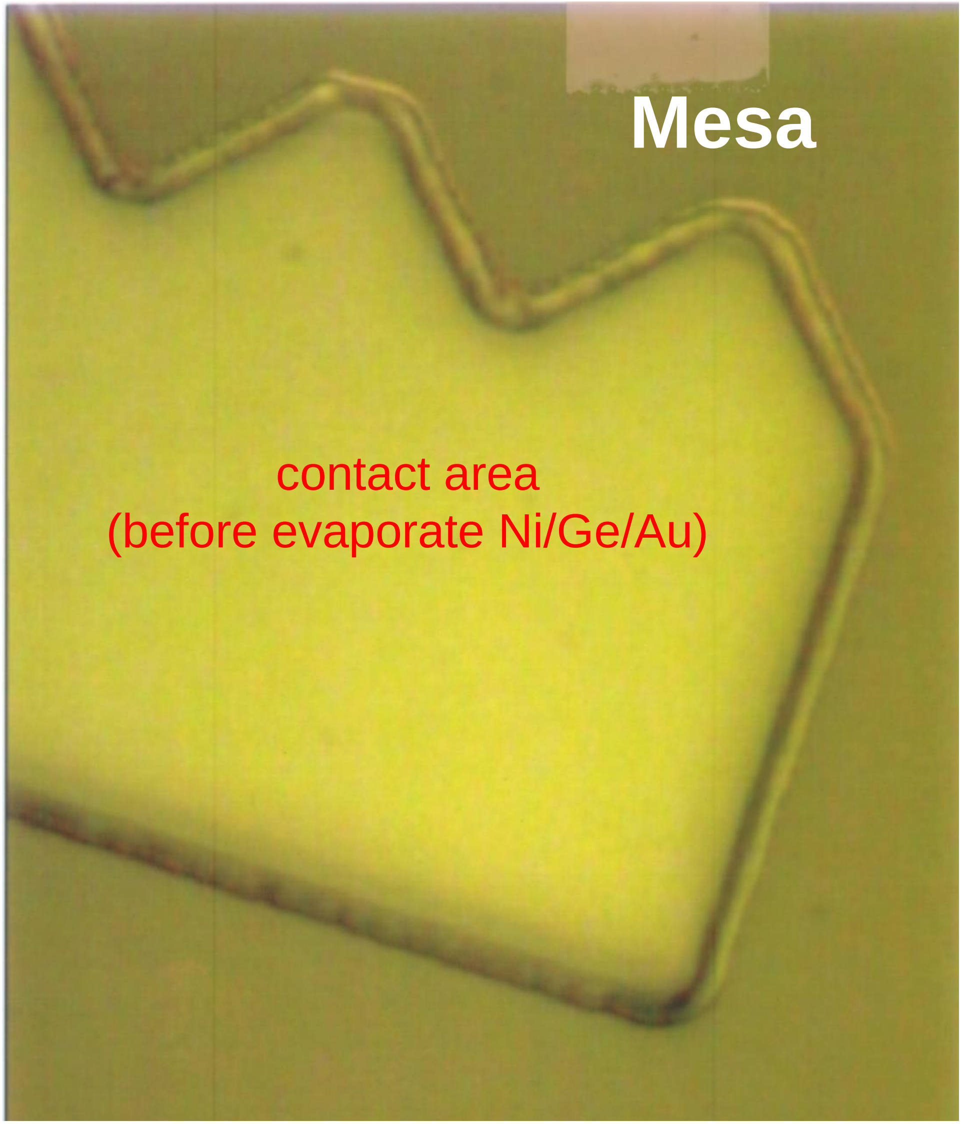


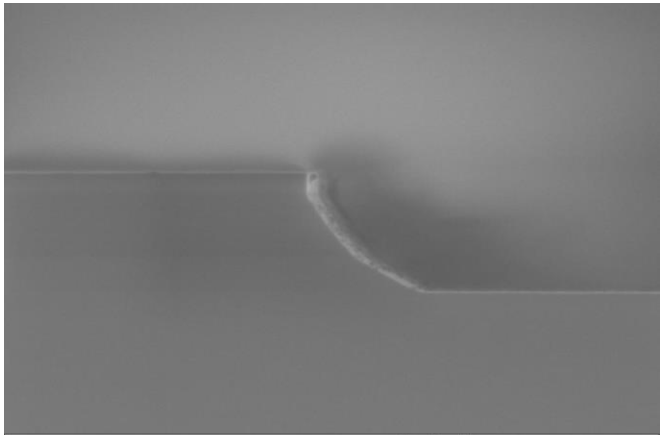


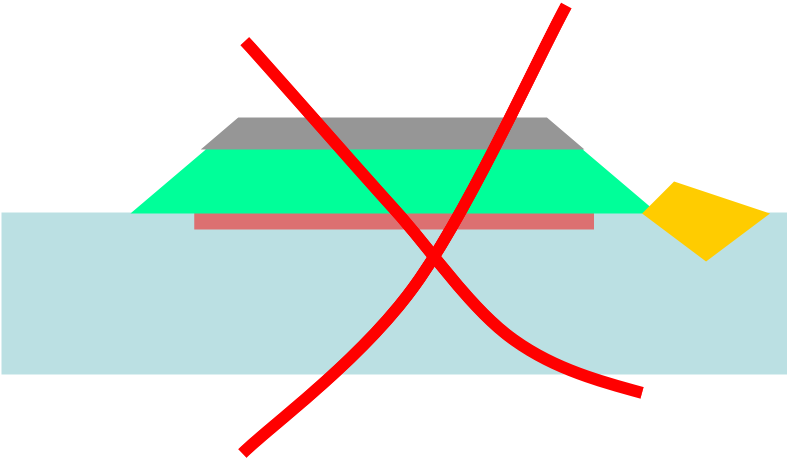
Straight sidewall is important

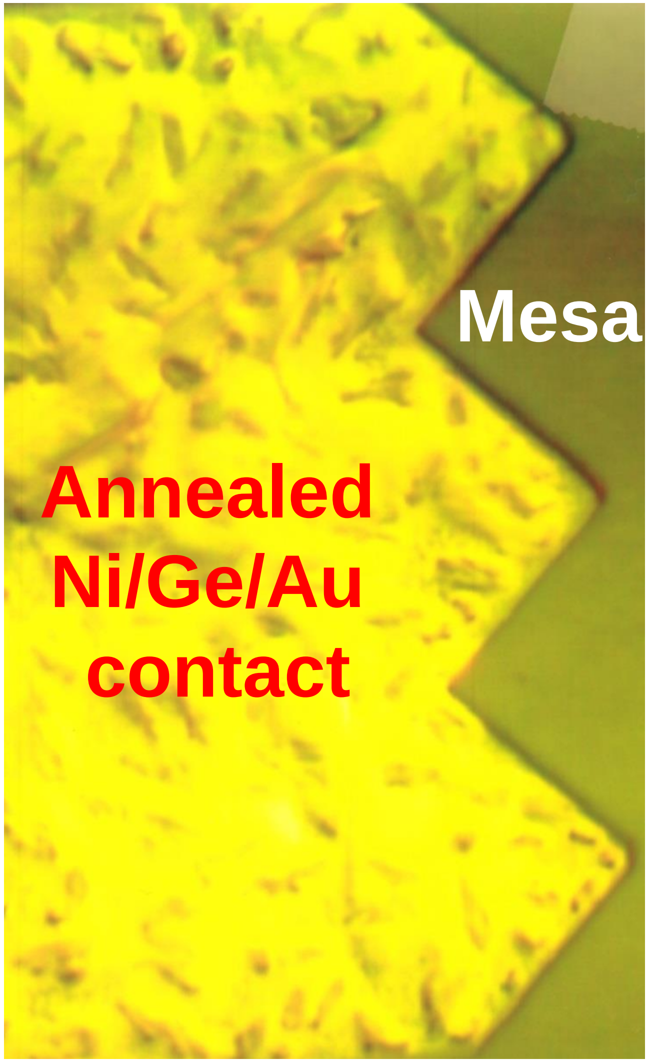


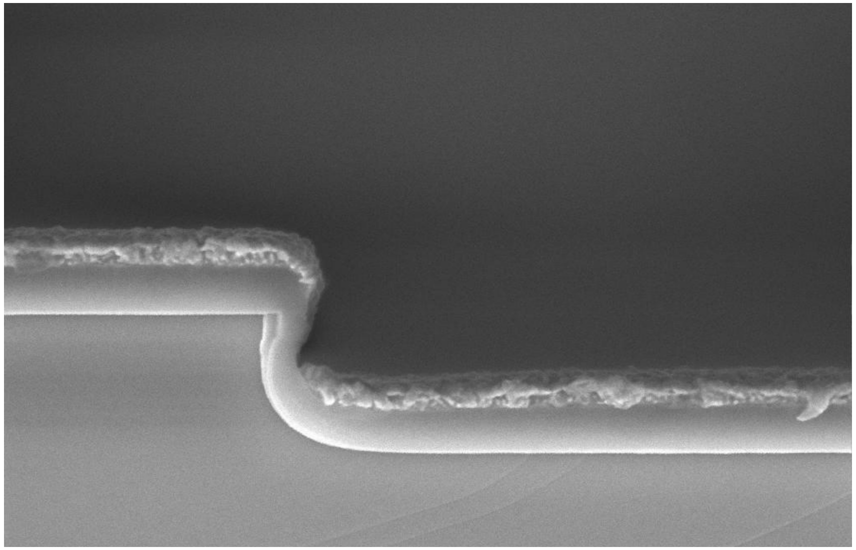



Mesa
contact area
(before evaporate Ni/Ge/Au)



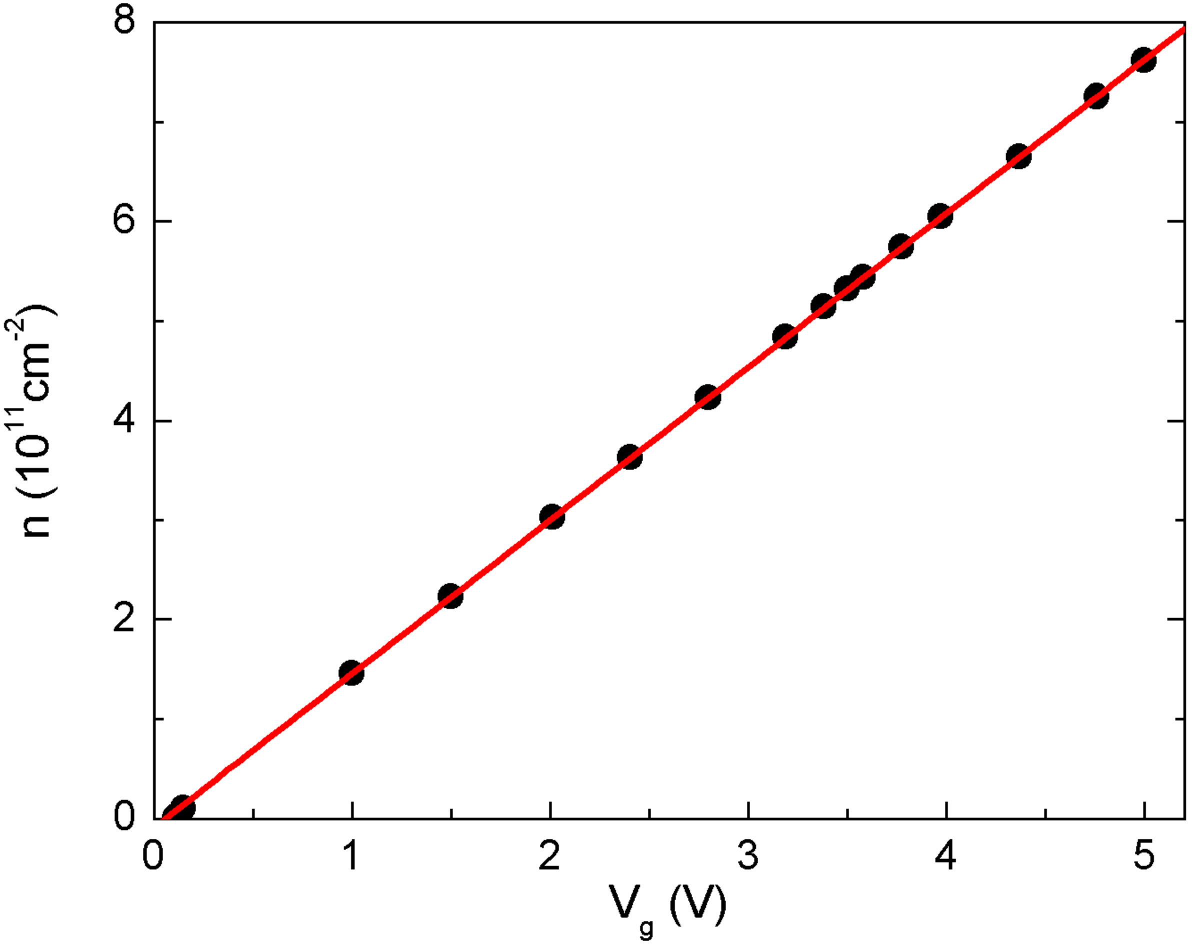




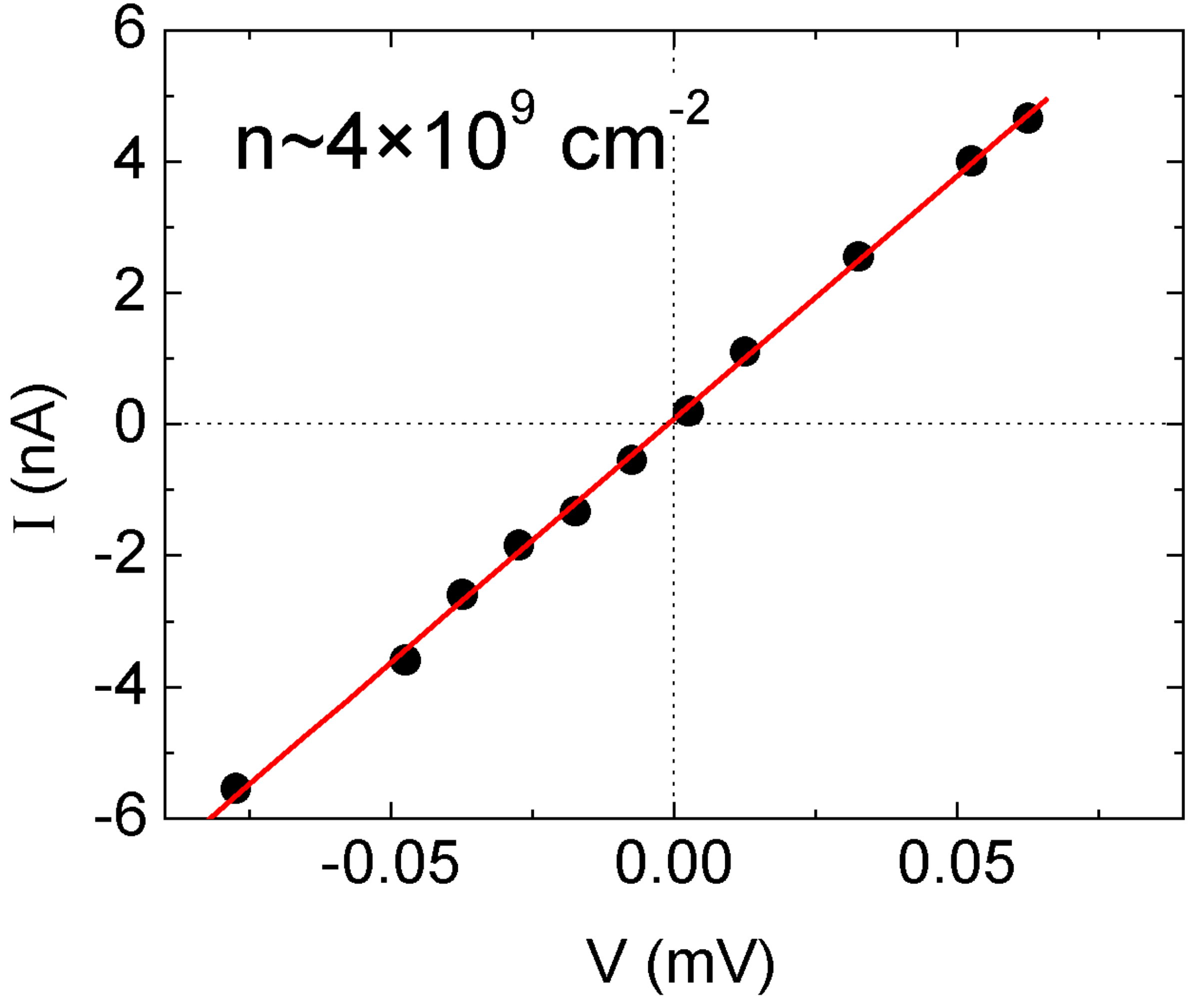


device works!

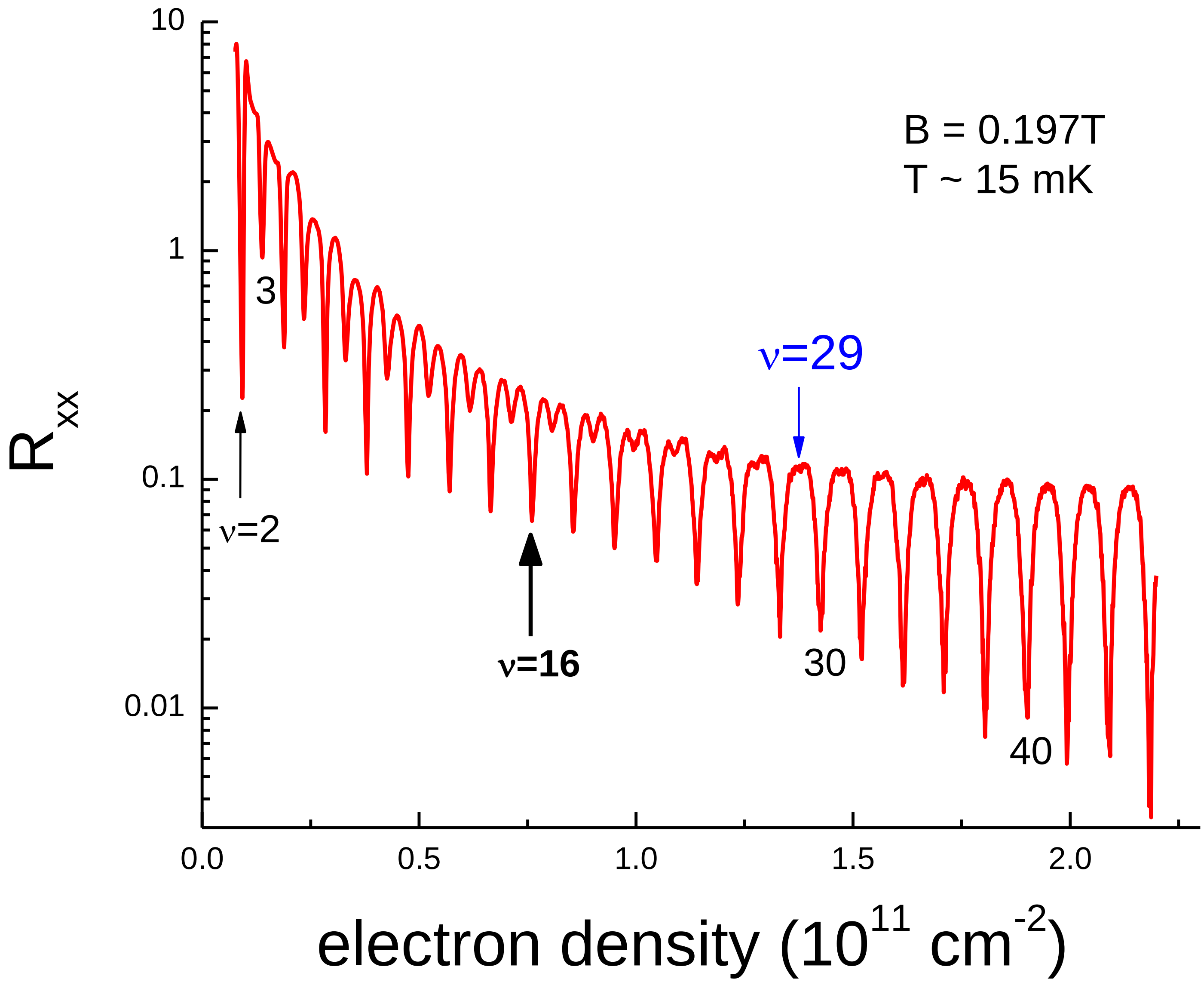
Very big density tunable range
~ 1x10^{9} to ~ 7.5x10^{11} cm^{-2}

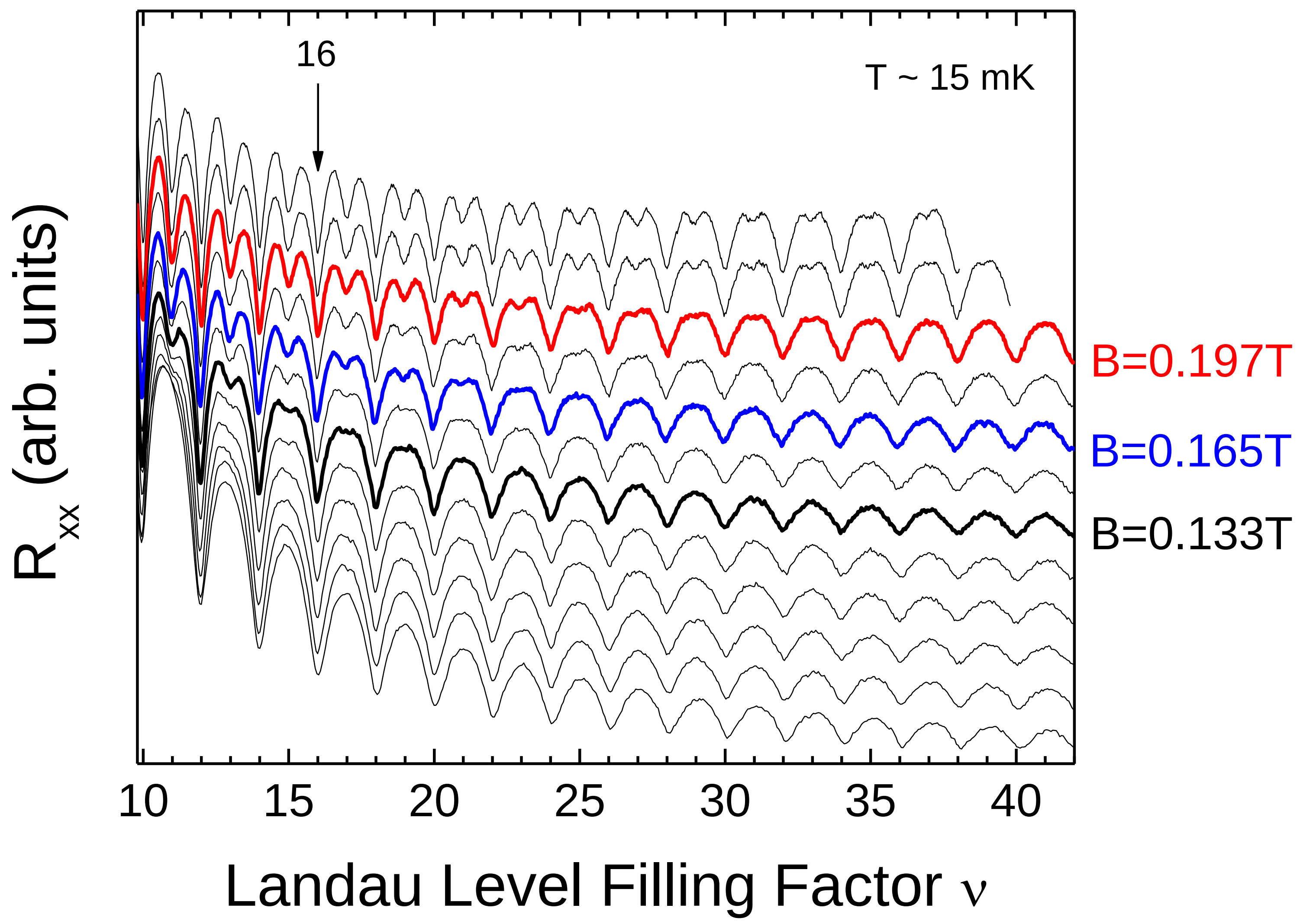


Linear I-V at very low densities

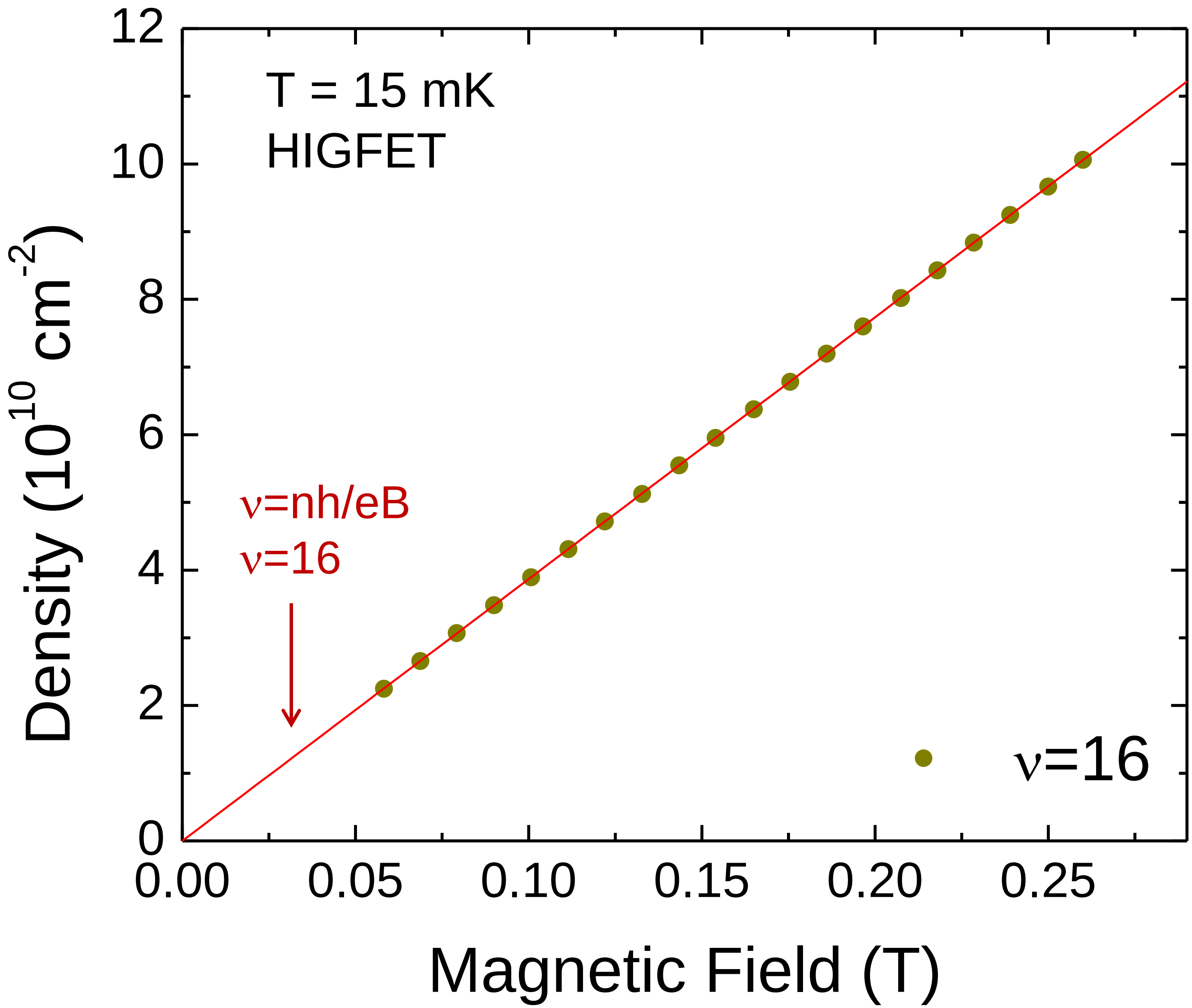


SdH oscillations at a low magnetic field

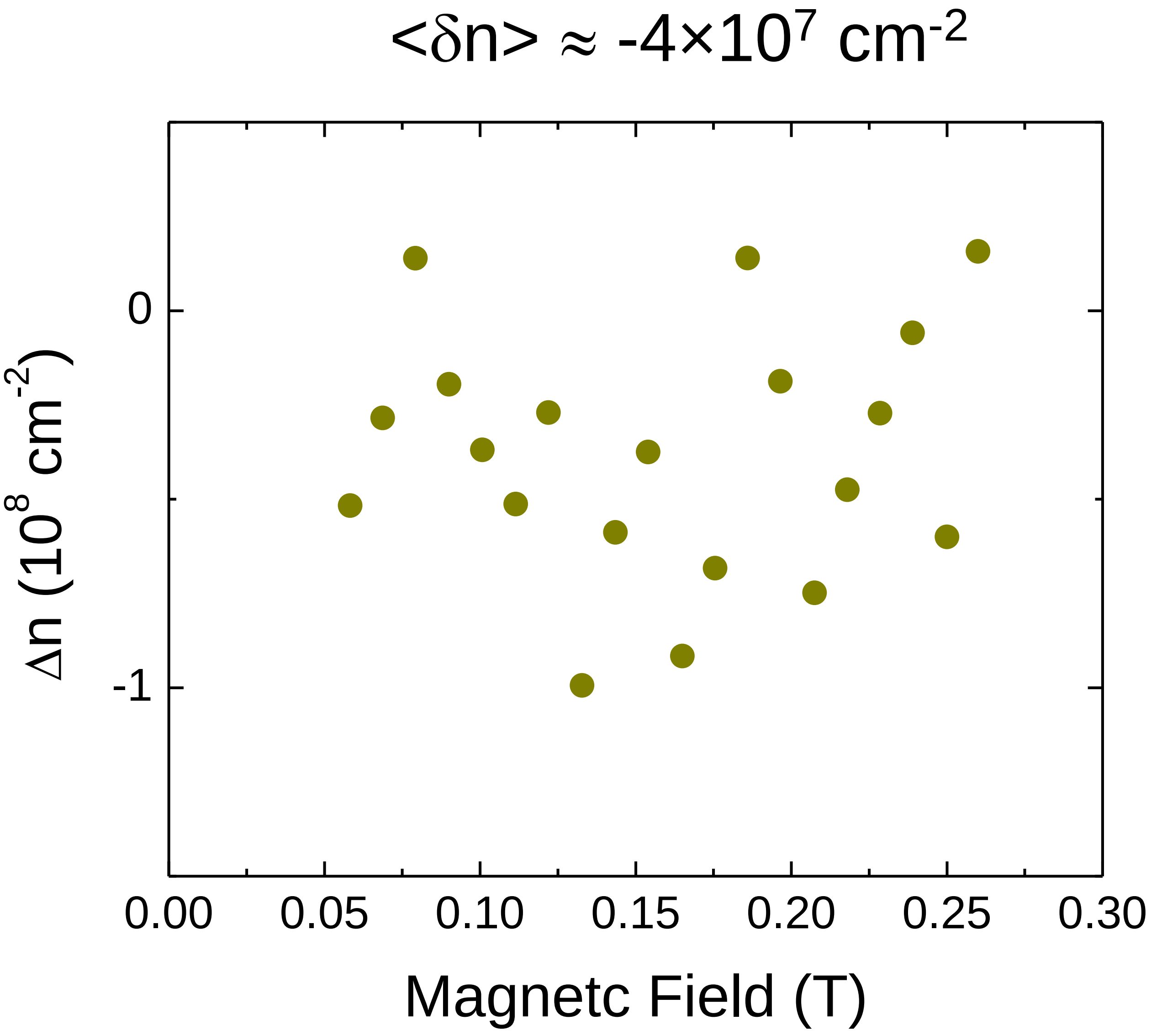




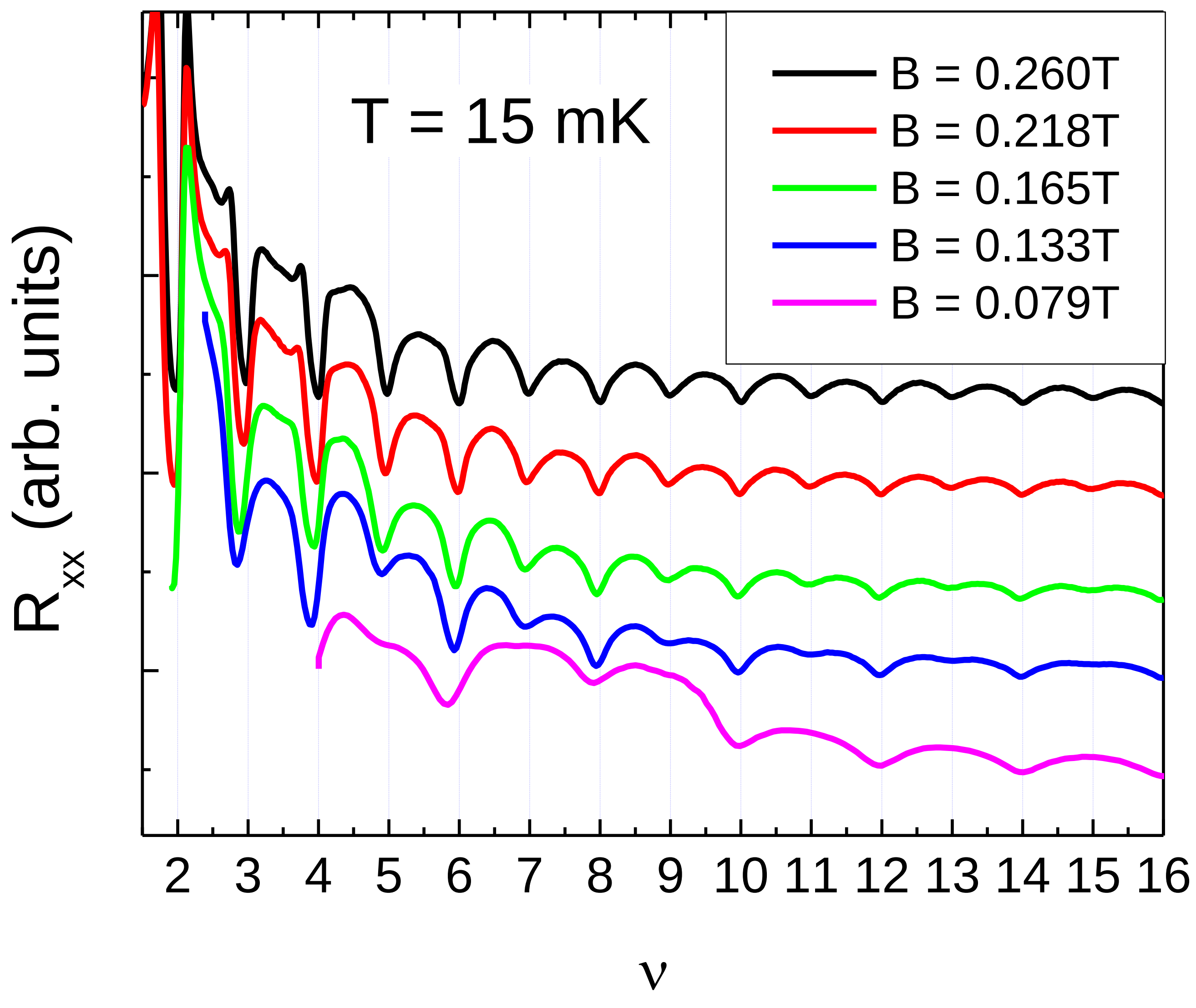
16
T ~ 15 mK
B=0.197T
B=0.165T
B=0.133T
R_{xx} (arb. units)
10
15
20
25
30
35
40
Landau Level Filling Factor ν

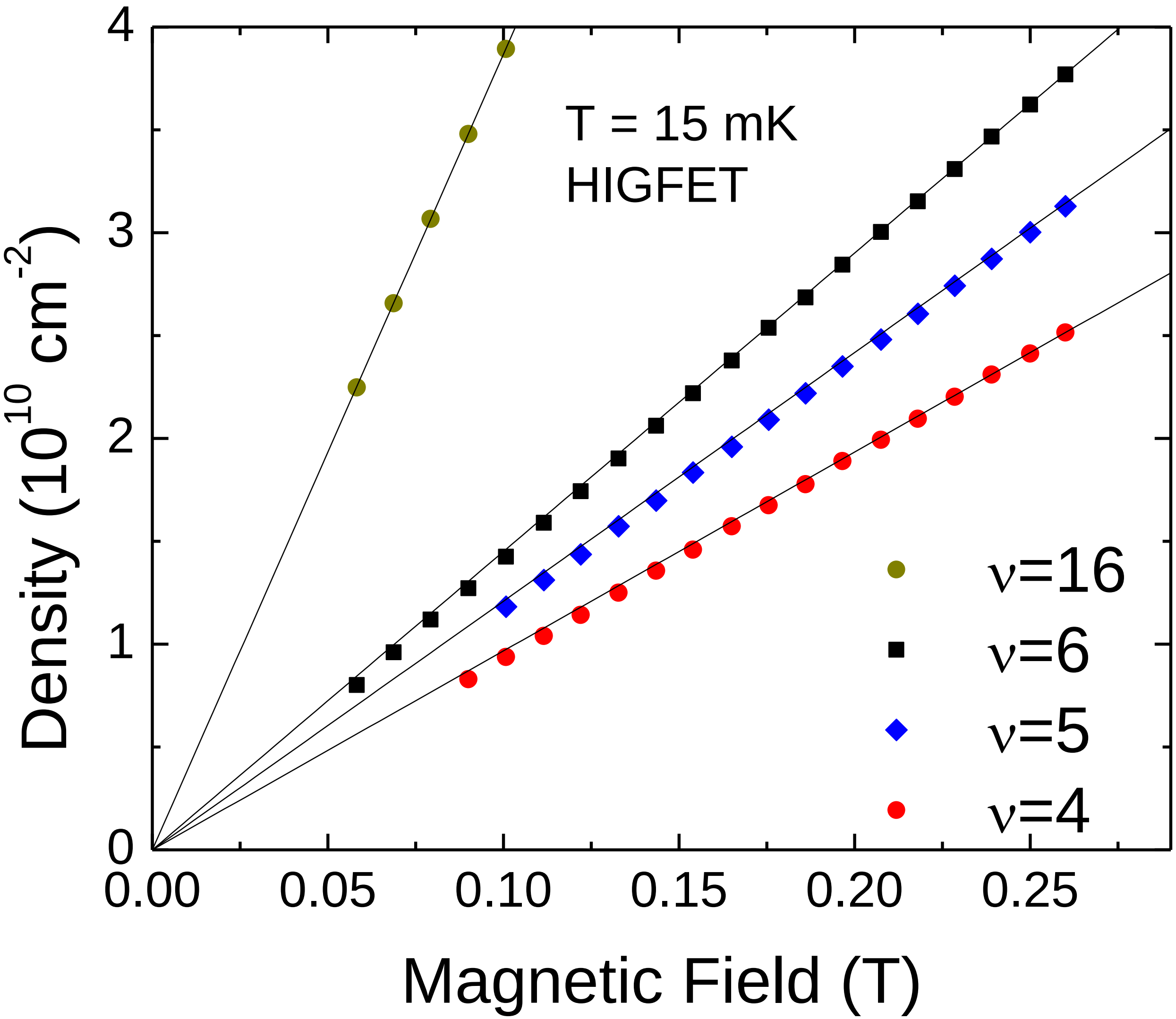


T = 15 mK
HIGFET
ν=nh/eB
ν=16
ν=16
Density (10^10 cm^-2)
Magnetic Field (T)
0
2
4
6
8
10
12
0.00
0.05
0.10
0.15
0.20
0.25



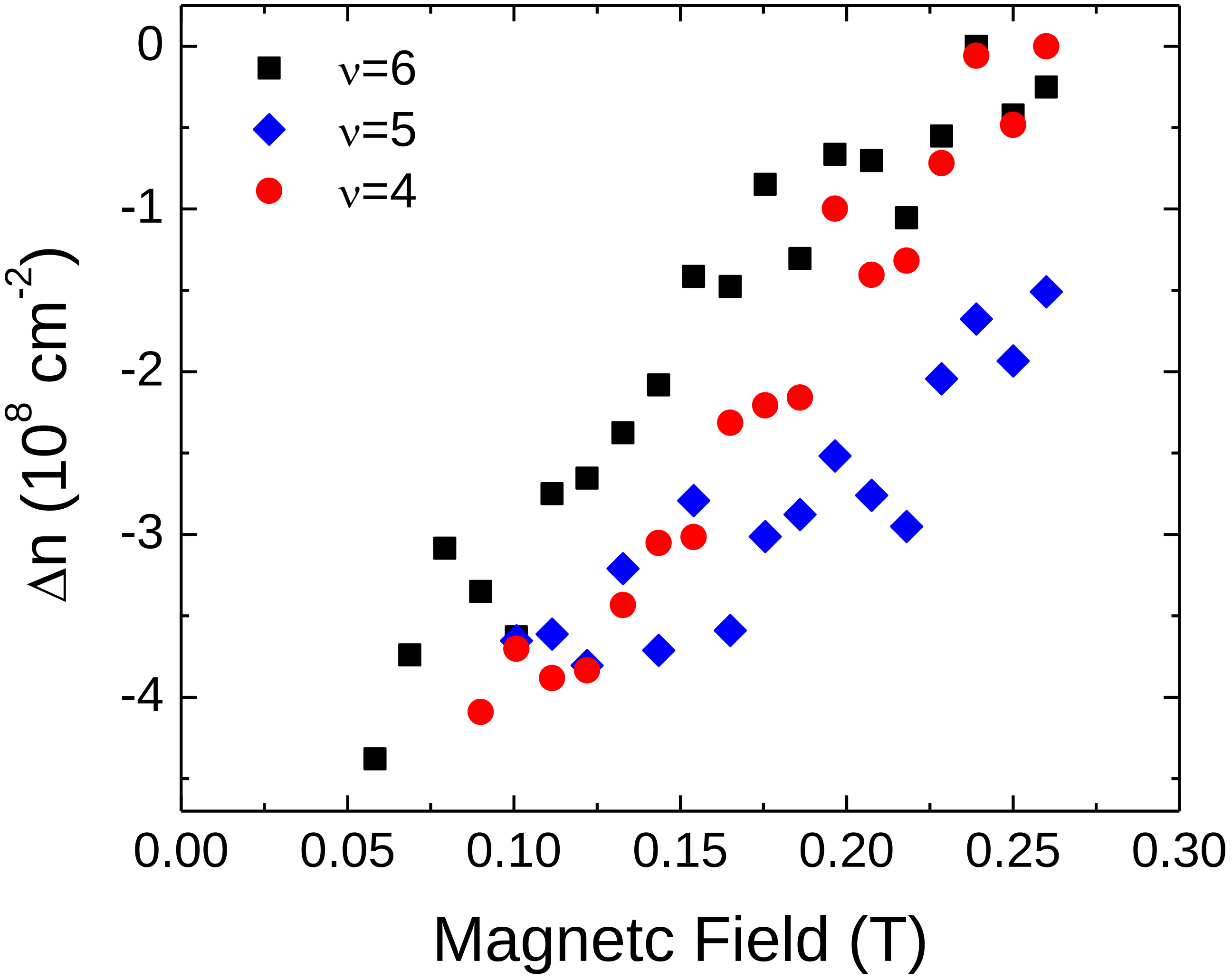
<δn> ≈ -4×10^7 cm^-2
0
-1
Δn (10^8 cm^-2)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Magnetc Field (T)

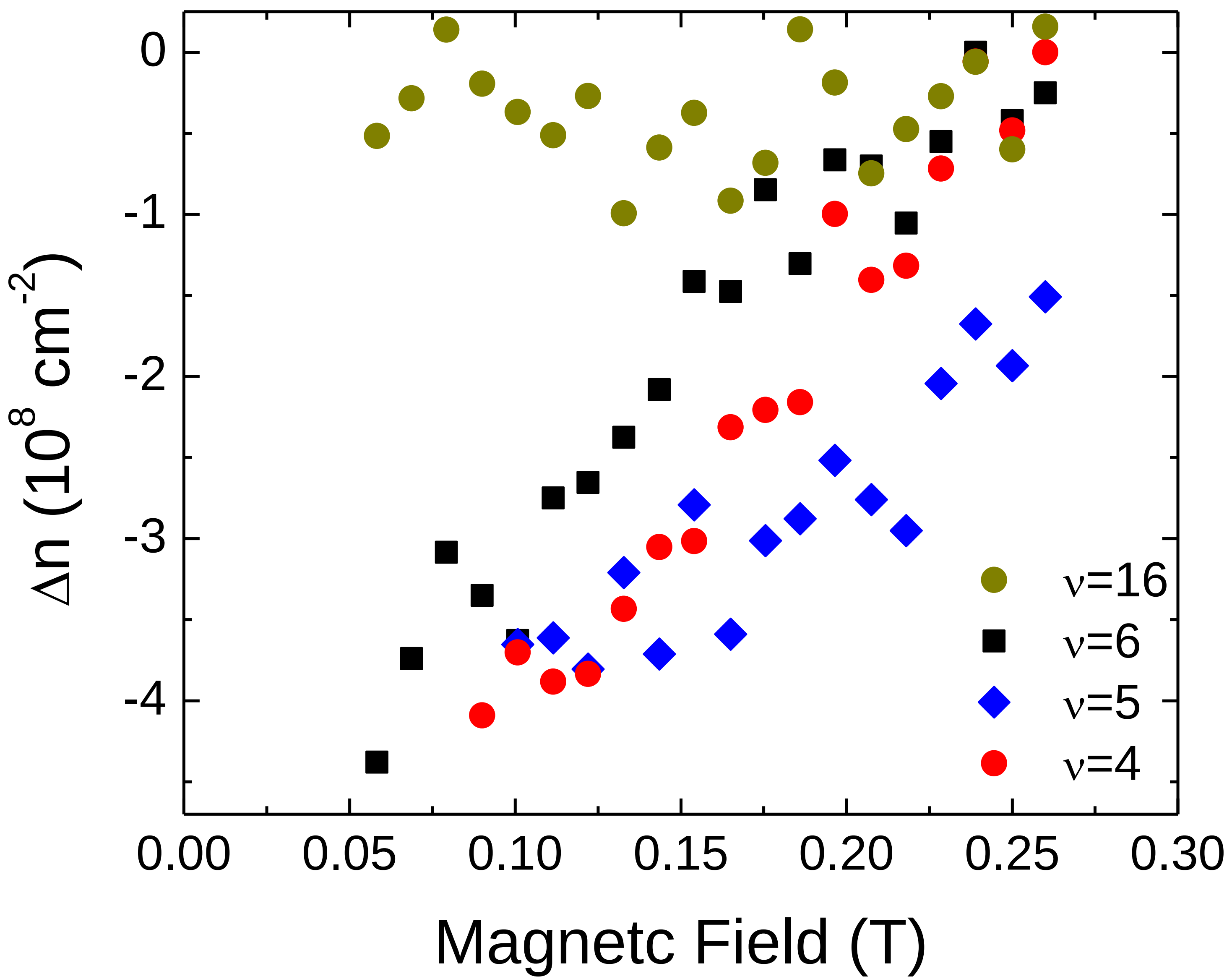

T = 15 mK
B = 0.260T
B = 0.218T
B = 0.165T
B = 0.133T
B = 0.079T
R_{xx} (arb. units)
ν
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16



T = 15 mK
HIGFET
ν=16
ν=6
ν=5
ν=4
Density (10^{10} cm^{-2})
Magnetic Field (T)
0
1
2
3
4
0.00
0.05
0.10
0.15
0.20
0.25

Observation of anti-floating in vanishing B field





0
-1
-2
-3
-4
Δn (10^8 cm^{-2})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Magnetc Field (T)
ν=16
ν=6
ν=5
ν=4

part I conclusion

In a high-quality HIGFET, anti-levitation of Landau levels is observed in vanishing magnetic fields.

This observation is in a good agreement with the theoretical prediction (C. Wang et al, PRB 2014).

- Observation of anti-levitation of Landau levels in vanishing magnetic fields

- Bloch oscillations in 2D superlattices

collaborators

S.K. Lyo and J.L. Reno
Sandia National Labs

D. Li and S.R.J. Brueck
Center for High Tech Materials, University of New Mexico

A. Kunold
Universidad Autónoma Metropolitana-Azcapotzalco, México

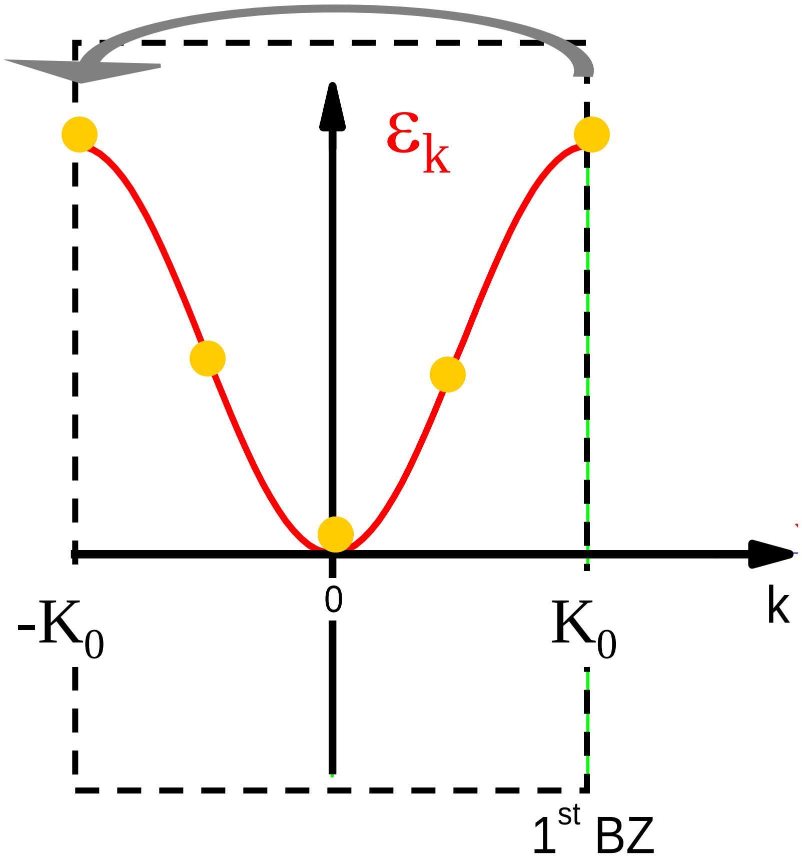
X. Feng and J. Kono
Rice University

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

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

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

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

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

$$\varepsilon_k \sim 1\text{- } \cos(ak)$$

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

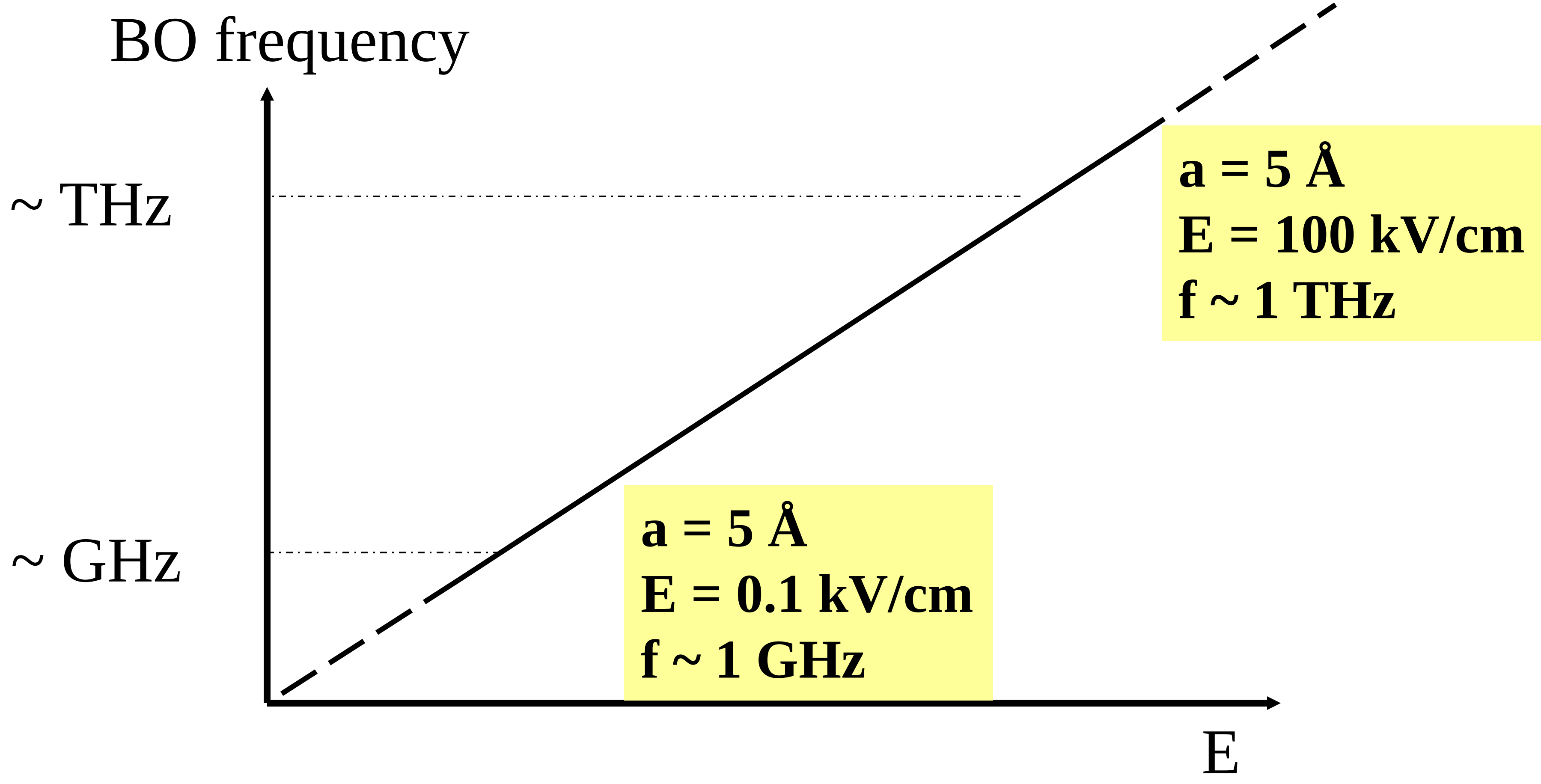
$$\mathbf{r \sim \cos(aeEt/\hbar) = \cos(2\pi ft)}$$

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

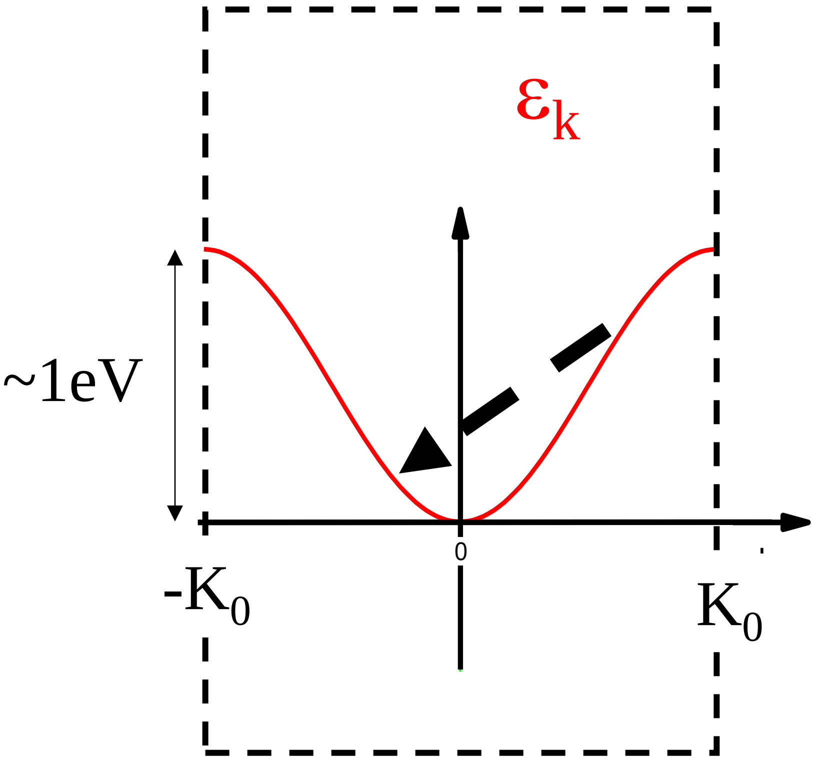
why Bloch oscillations (BO) ?

- THz application – frequency tunable

$$f = aeE/h$$



issues in 3D crystal

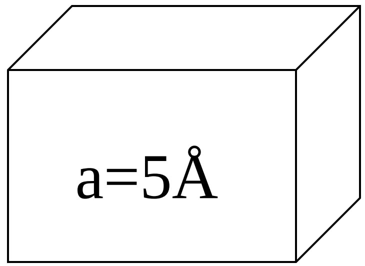


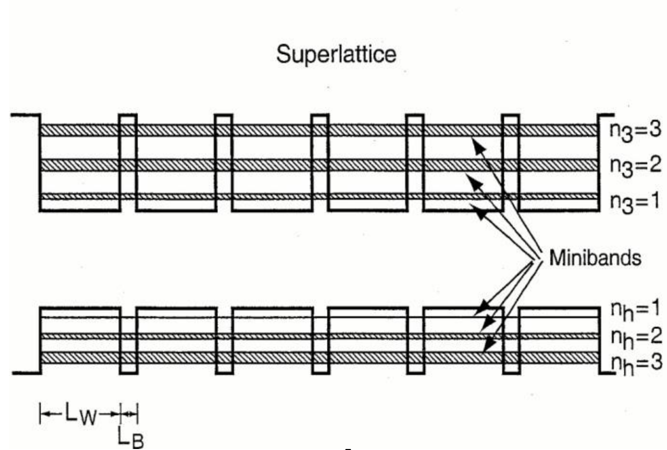
- Very high electric field
- Electron is scattered before it can complete a full oscillation

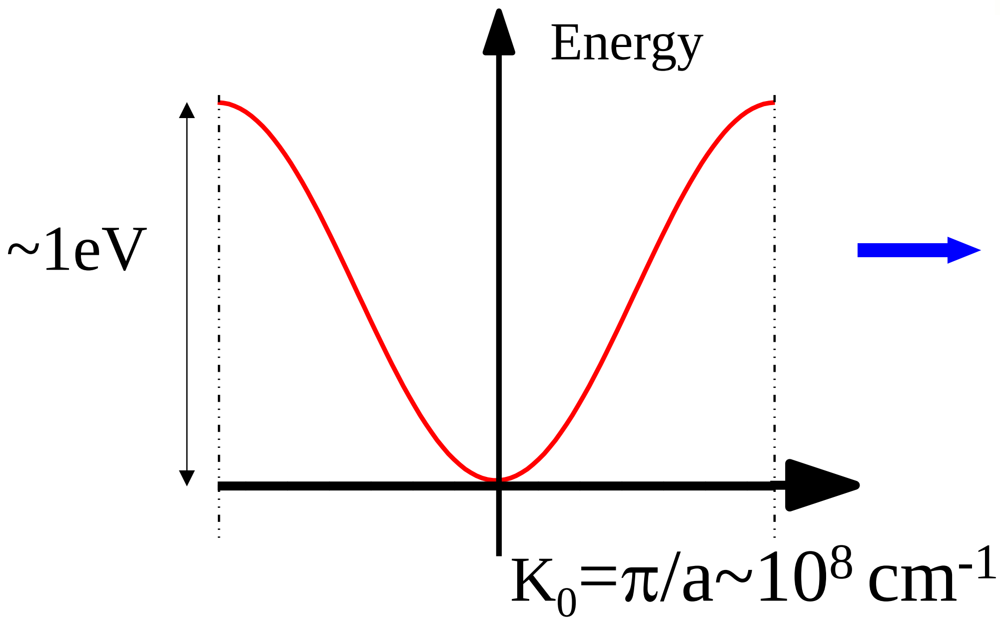
1D vertical superlattice

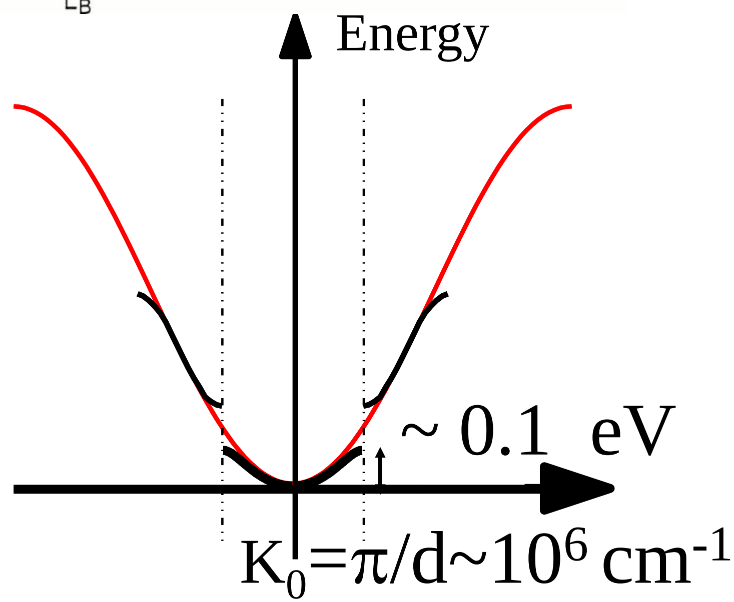
Esaki and Tsu, 1975

3D crystal









issues in 1D vertical superlattice

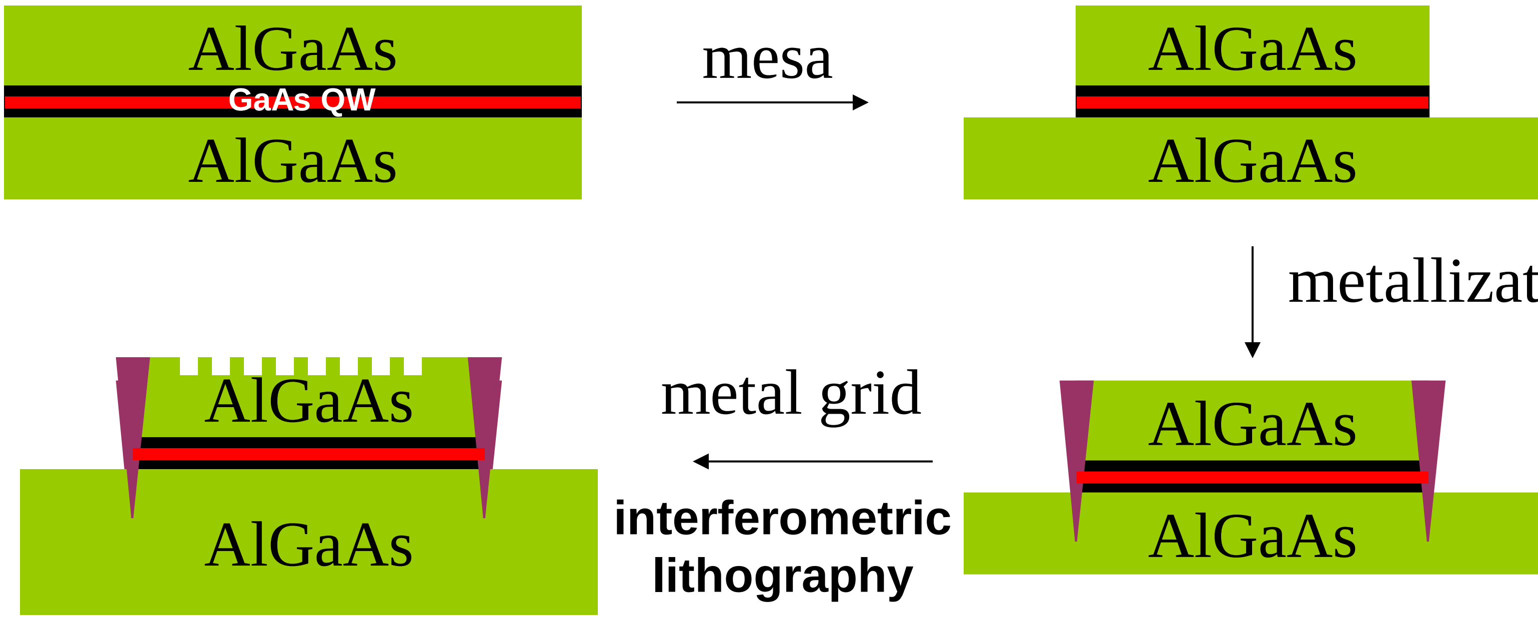
- formation of high electric field domains
- electron – phonon scattering
- impurity scattering
  - surface roughness scattering
- ….

2D quantum “dot” superlattice (QDSL)

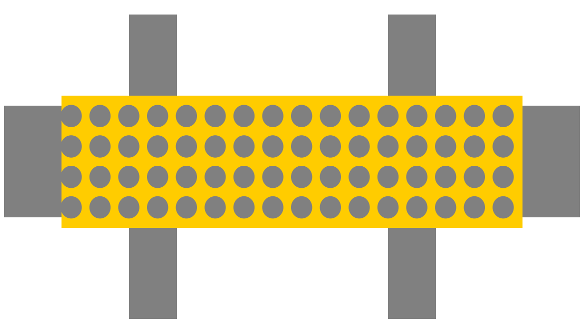
I.A. Dmitriev and R.A. Suris, Semiconductors 35, 212 (2001).

- 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

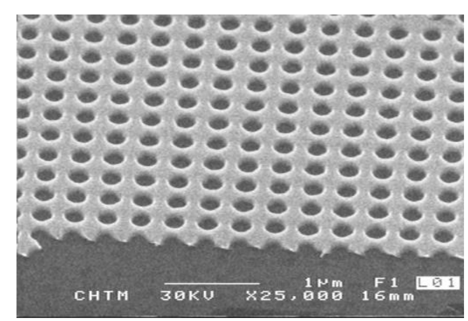
sample fabrication

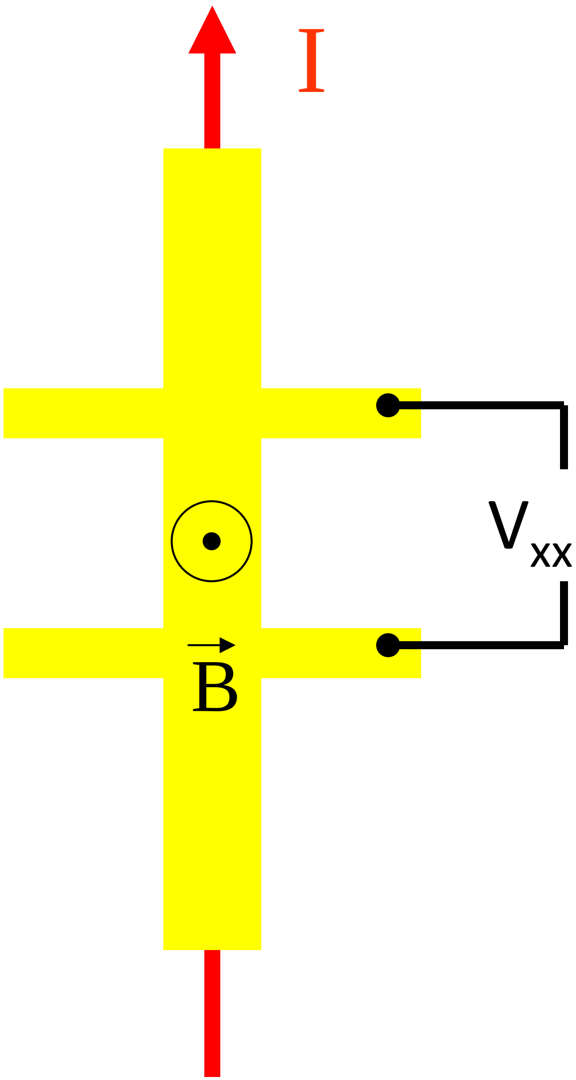


Top view



SEM picture

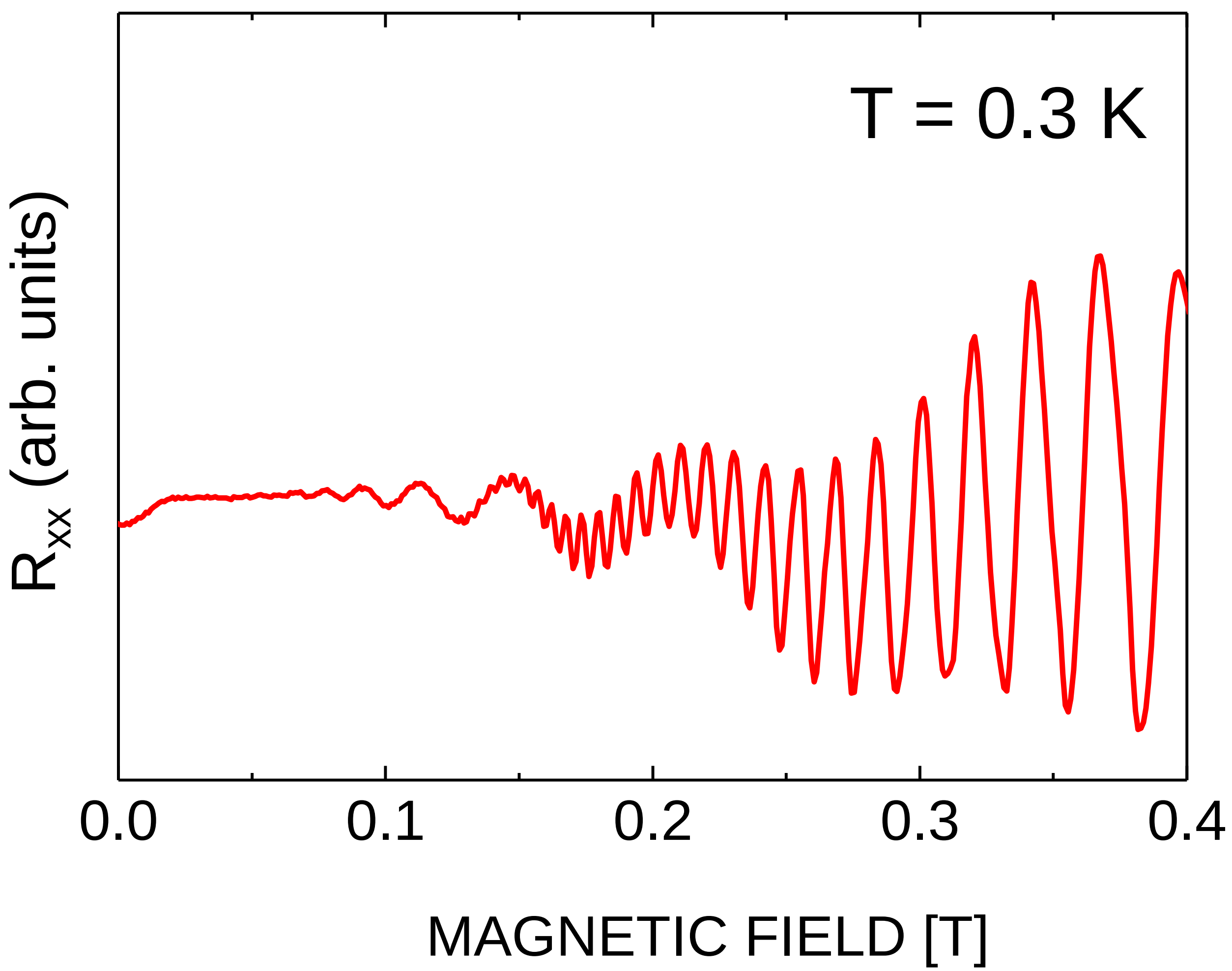


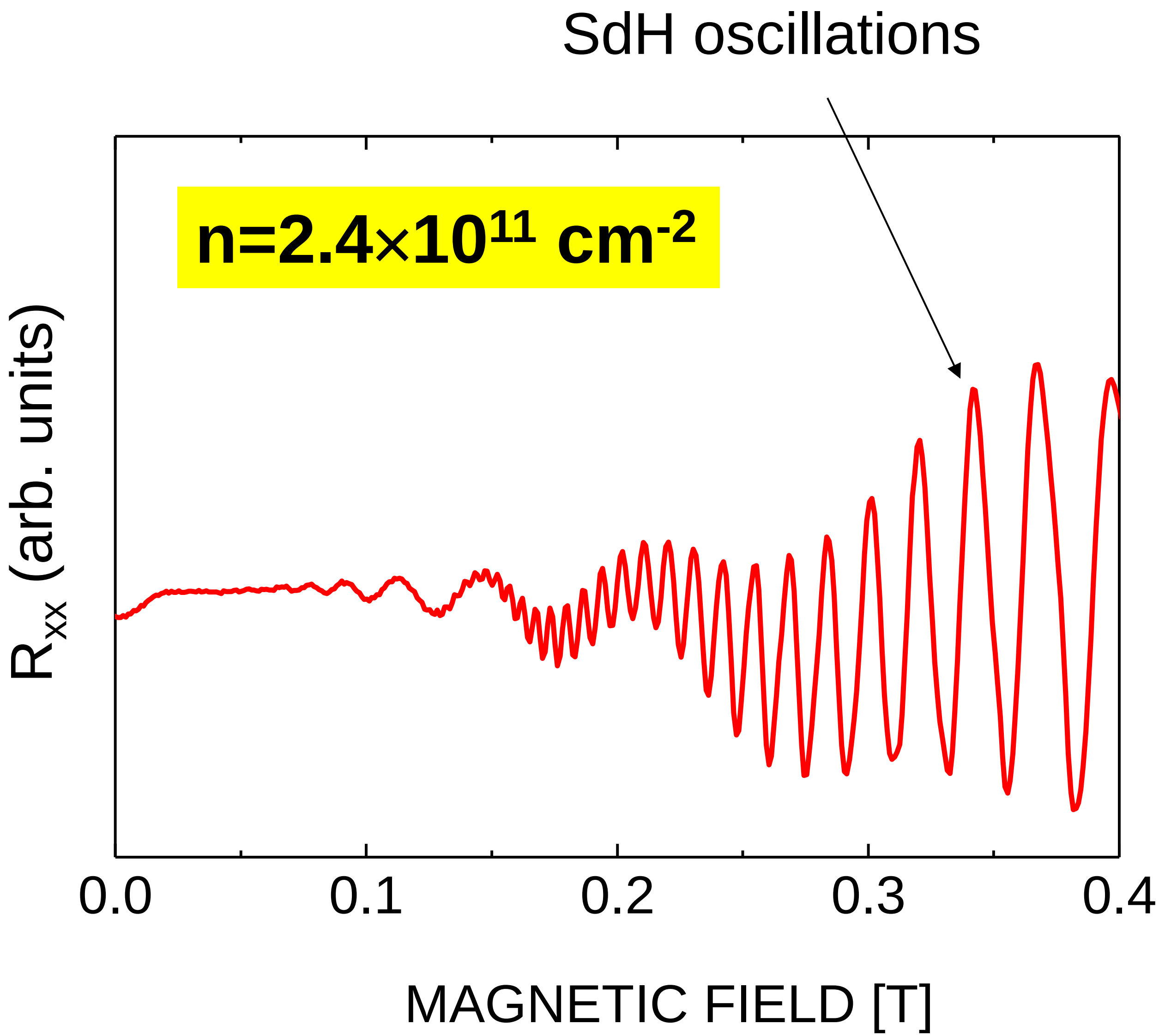


transport coefficients:

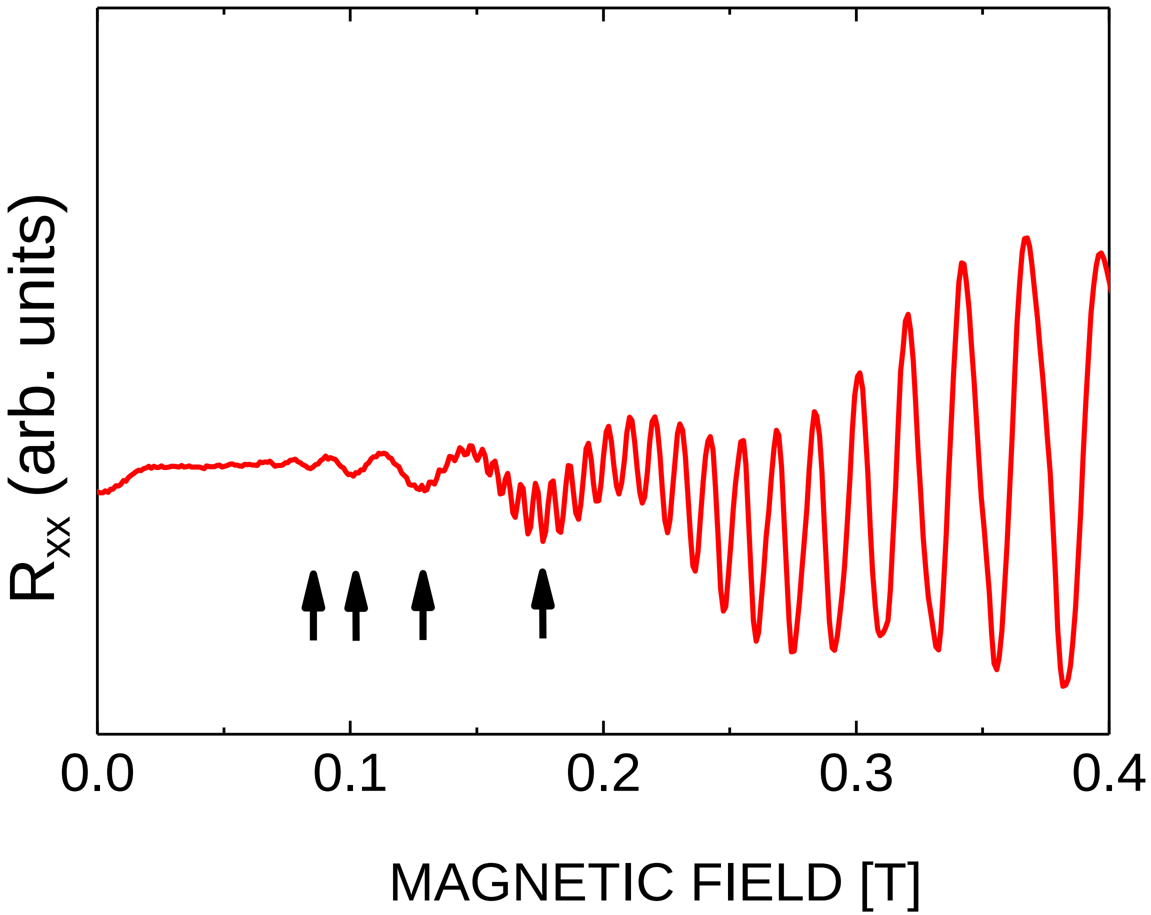
$$R_{xx} = V_{xx}/I$$

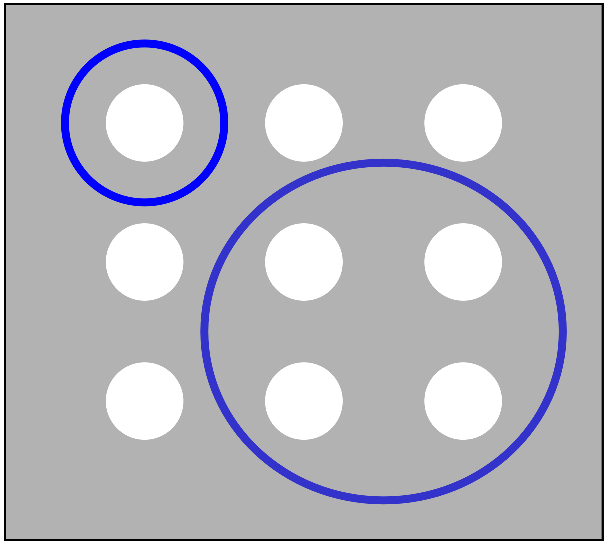
sample characterization – magneto-transport

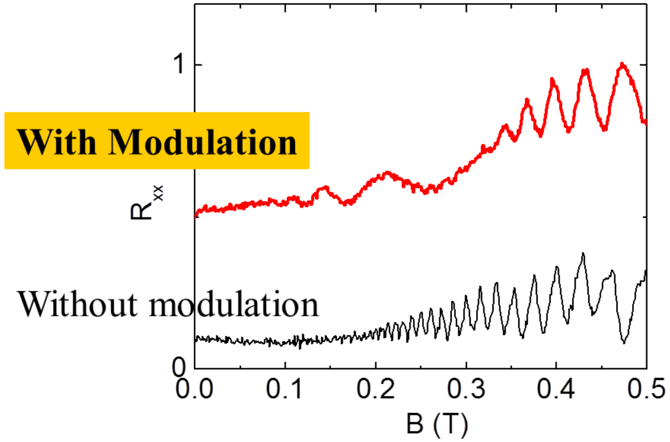



SdH oscillations
n=2.4×10^11 cm^-2
R_xx (arb. units)
0.0
0.1
0.2
0.3
0.4
MAGNETIC FIELD [T]

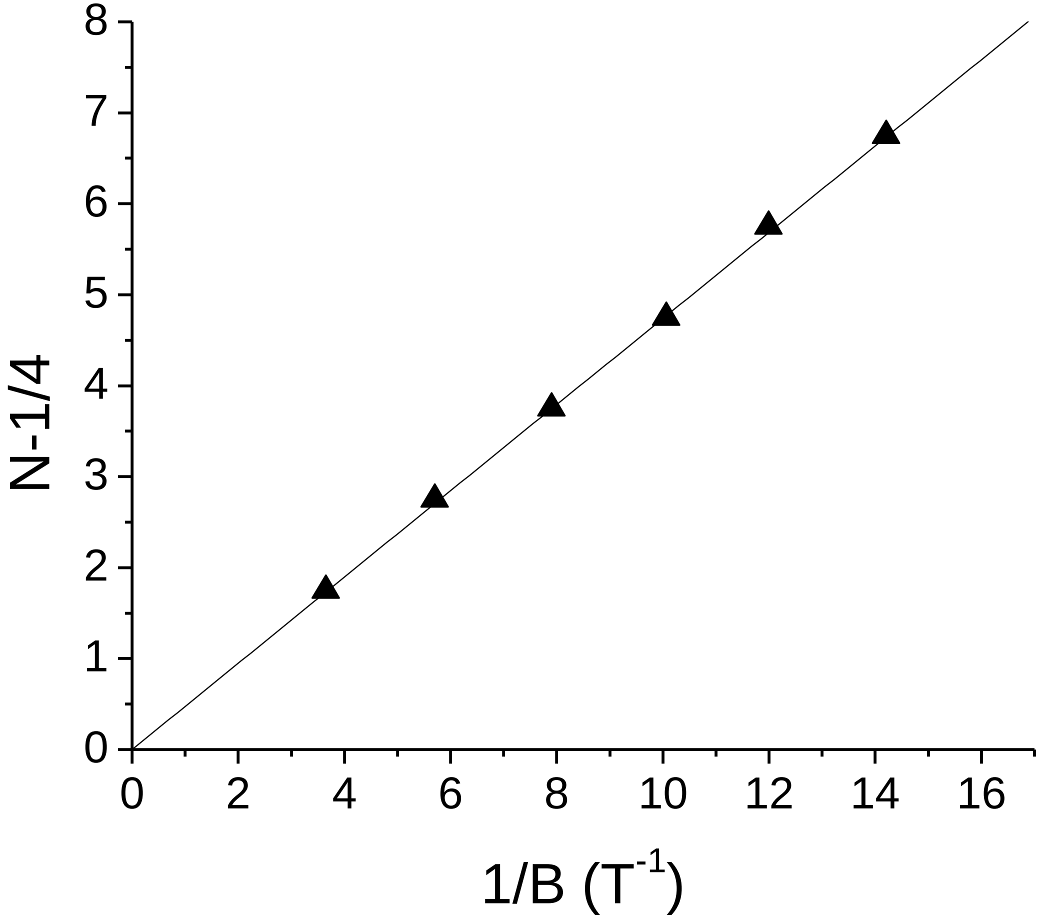
geometric oscillations







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

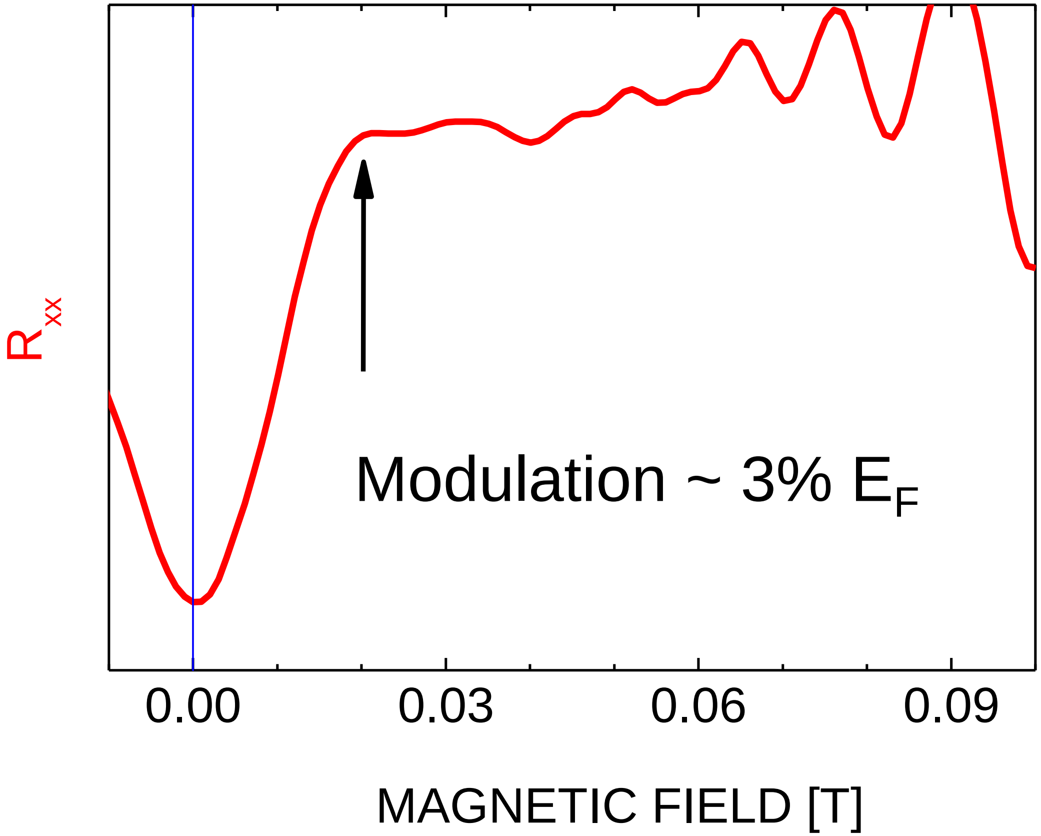
k_F – Fermi wavefactor

From slope,

d ~ 340 nm

Weiss et al, PRL 66, 2790 (1991)

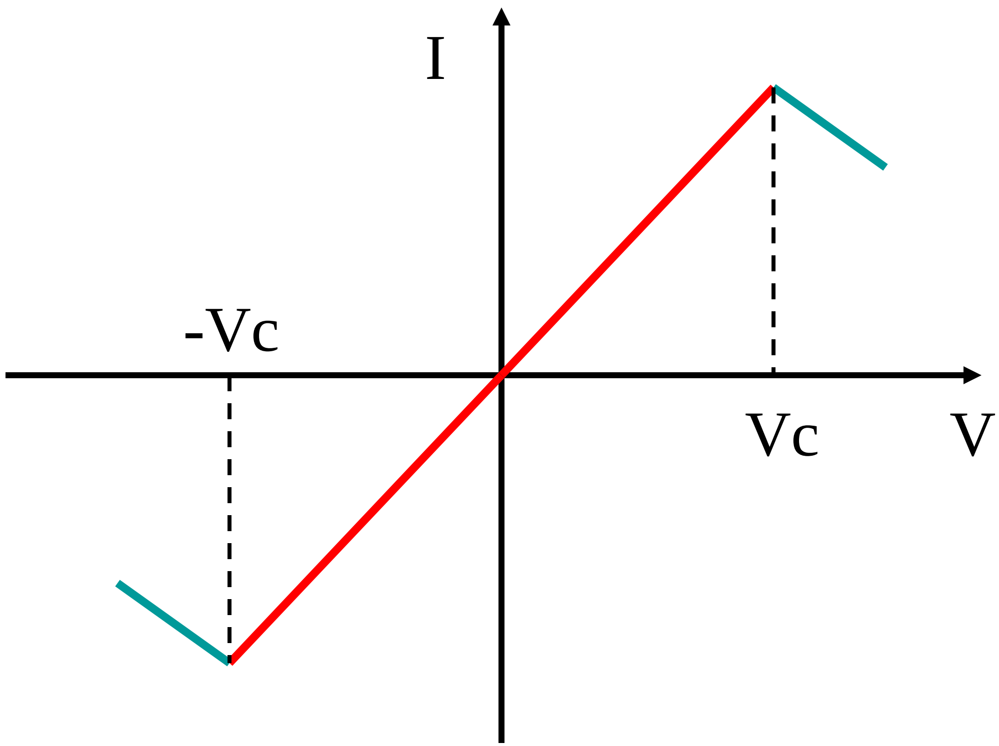
positive magneto-resistance around B = 0



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

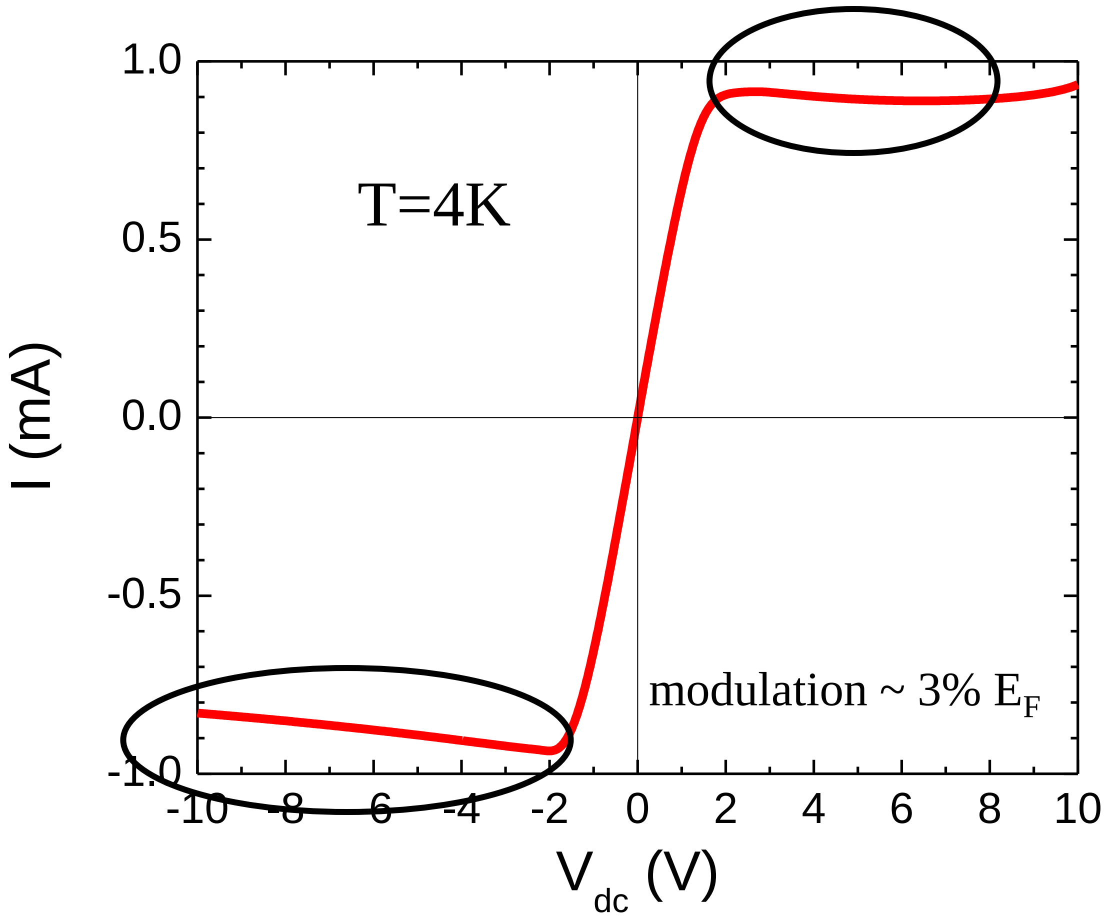
evidence of Bloch oscillations in 2D QDSL

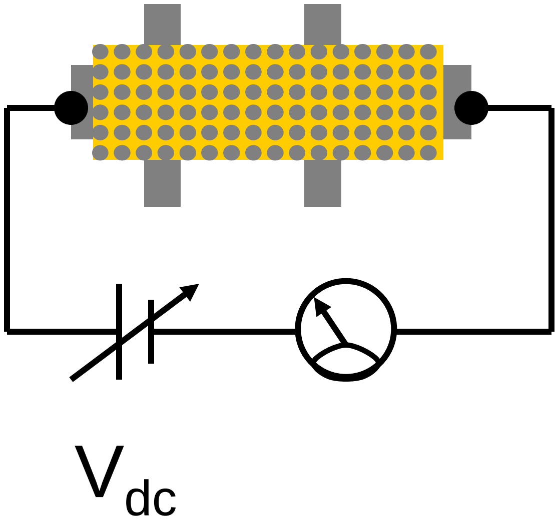
one of the signatures for Bloch oscillations is negative differential conductance (NDC)

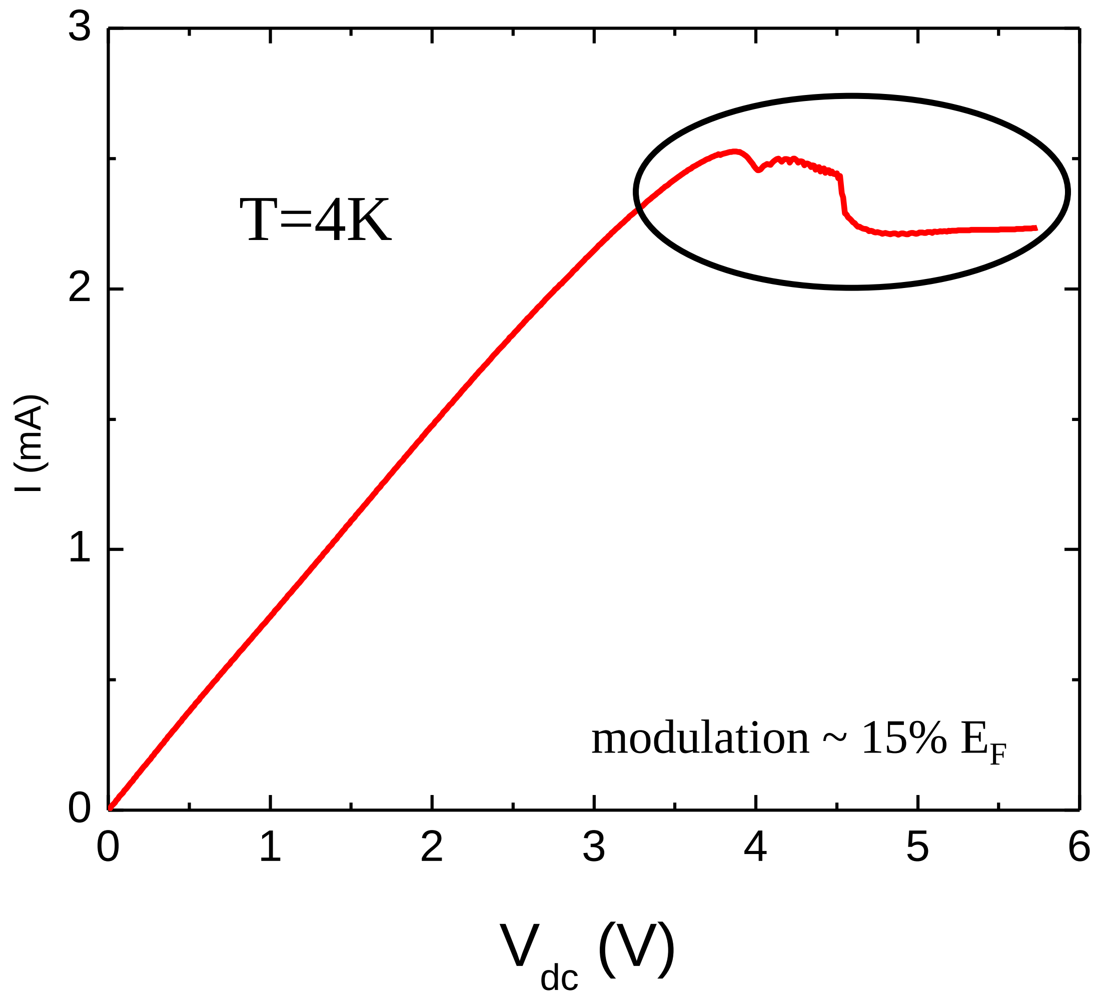


I – V measurement in 2D QDSL

NDC observed

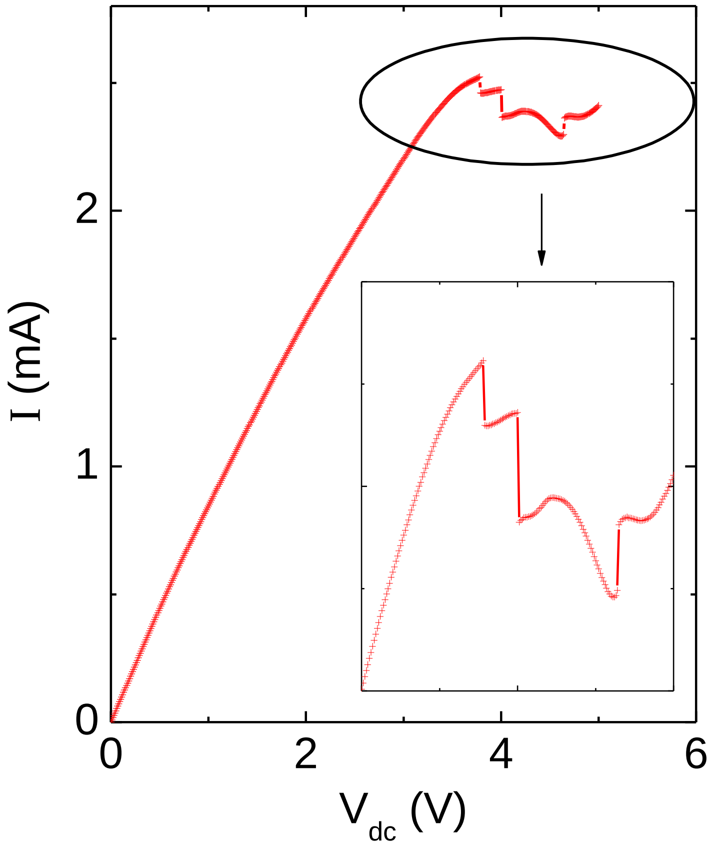






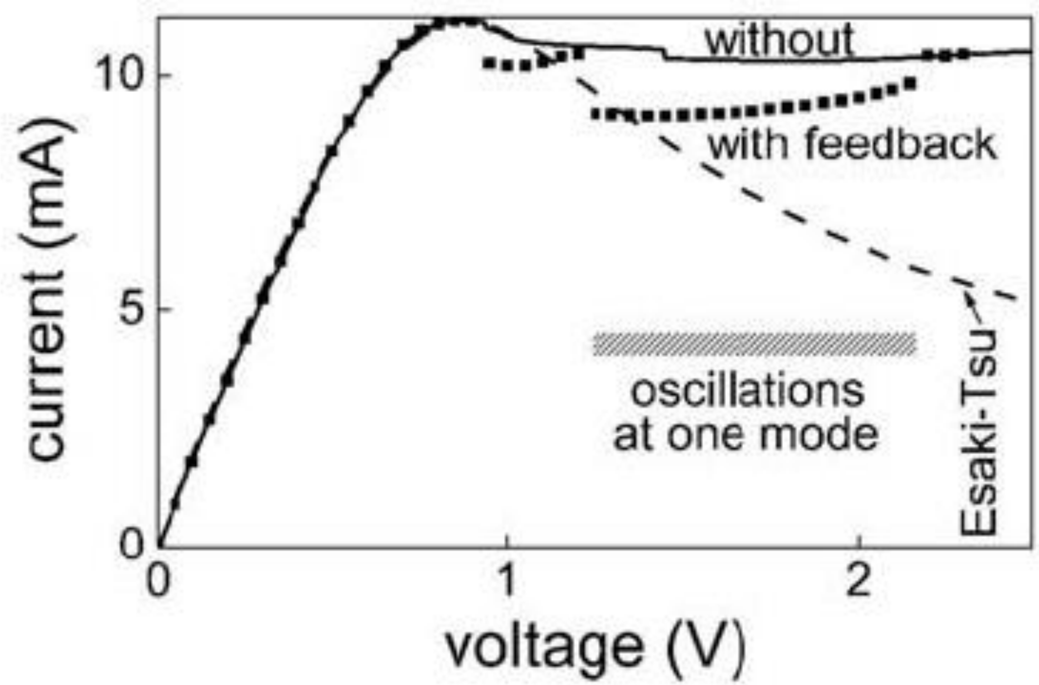
3
2
1
0
0
1
2
3
4
5
6
I (mA)
V_{dc} (V)
T=4K
modulation ~ 15% E_F

in yet another sample



Similar current jumps were also observed in:

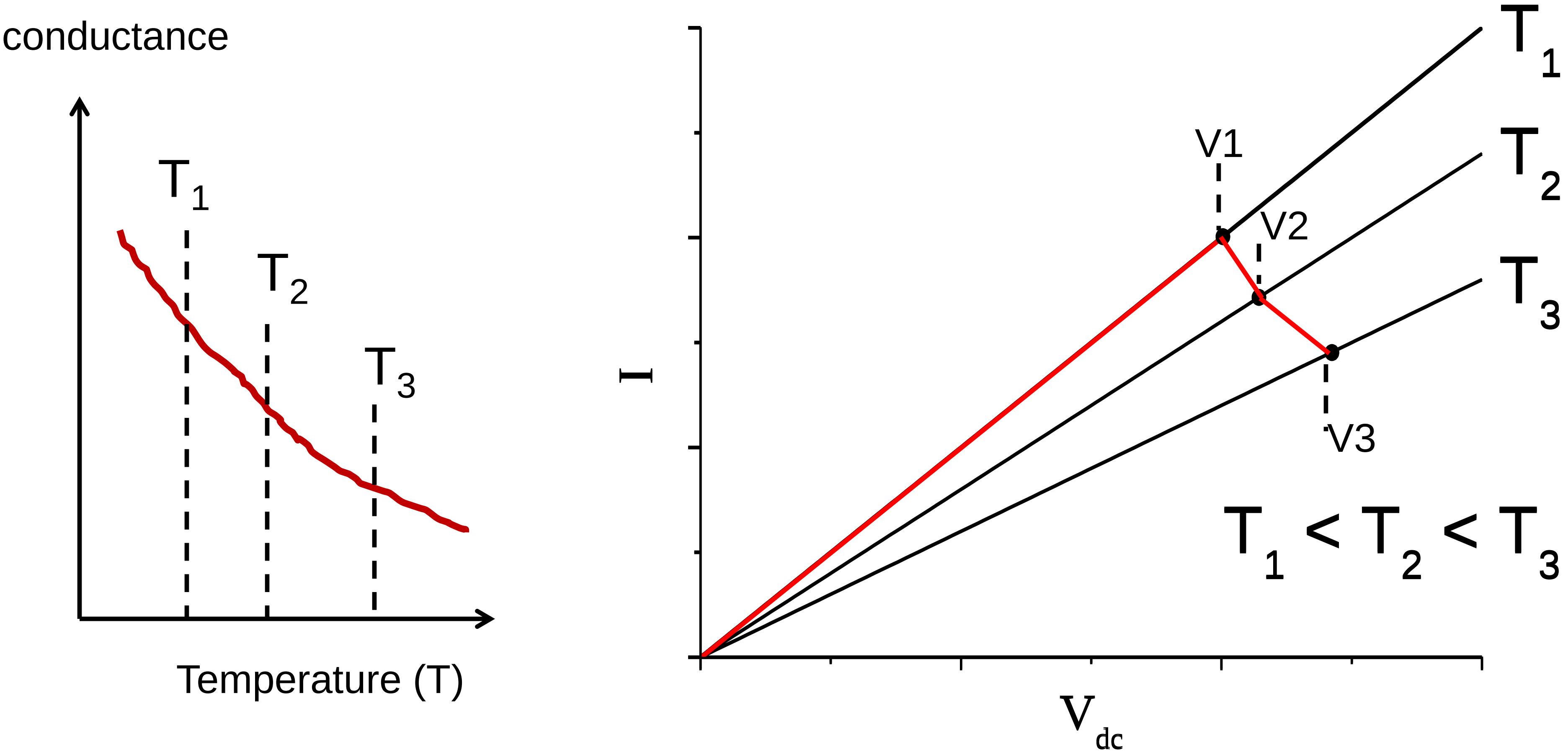
- **GaAs/AlAs 1D superlattices** (Renk et al, 2005)



physical origin of NDC ?

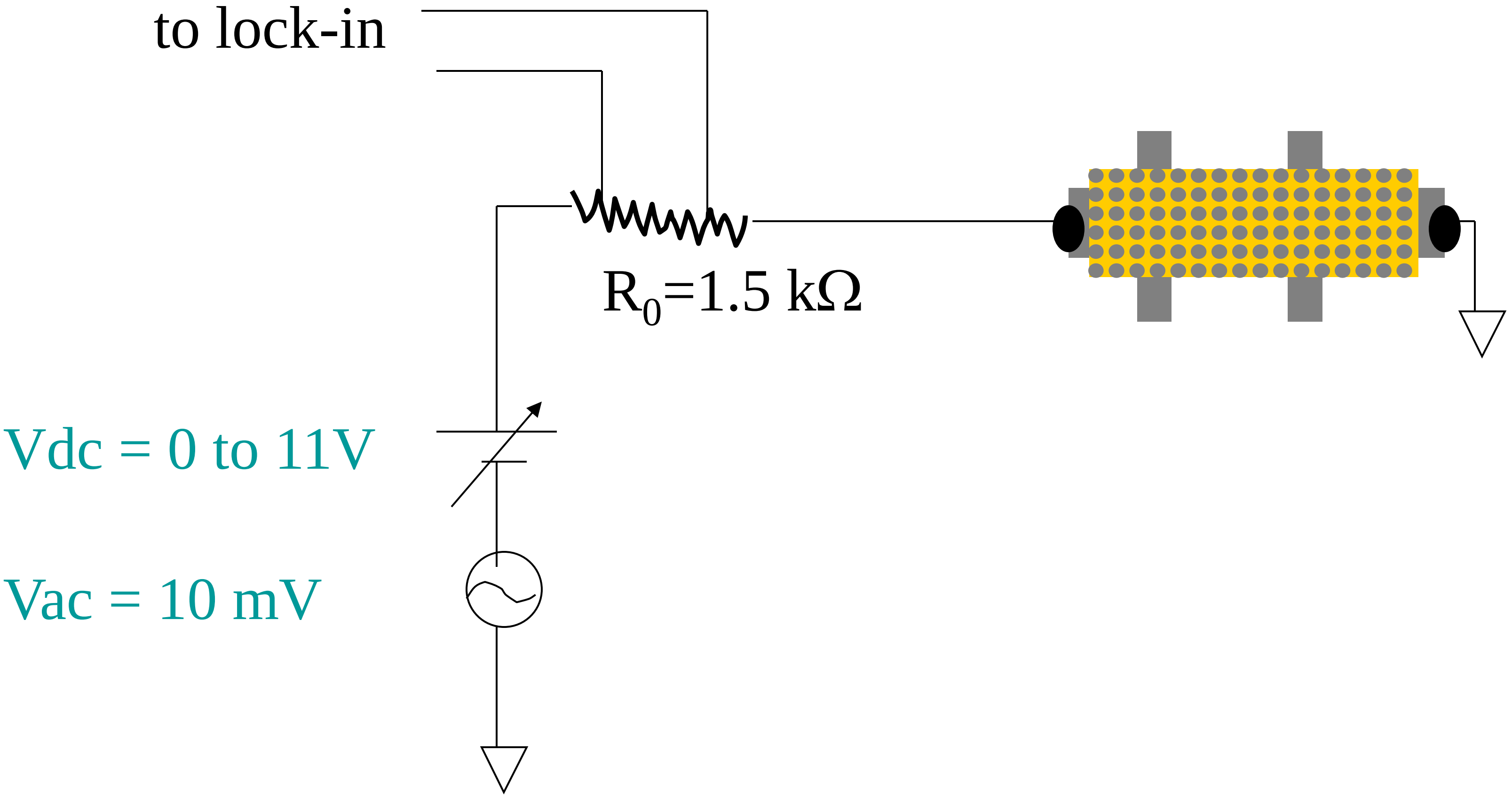
- Bloch oscillations?
- thermal runaway?
- ….

thermal runaway



Temperature dependent conductance can give rise to an apparent NDC

(Suggested by Mark Lee)

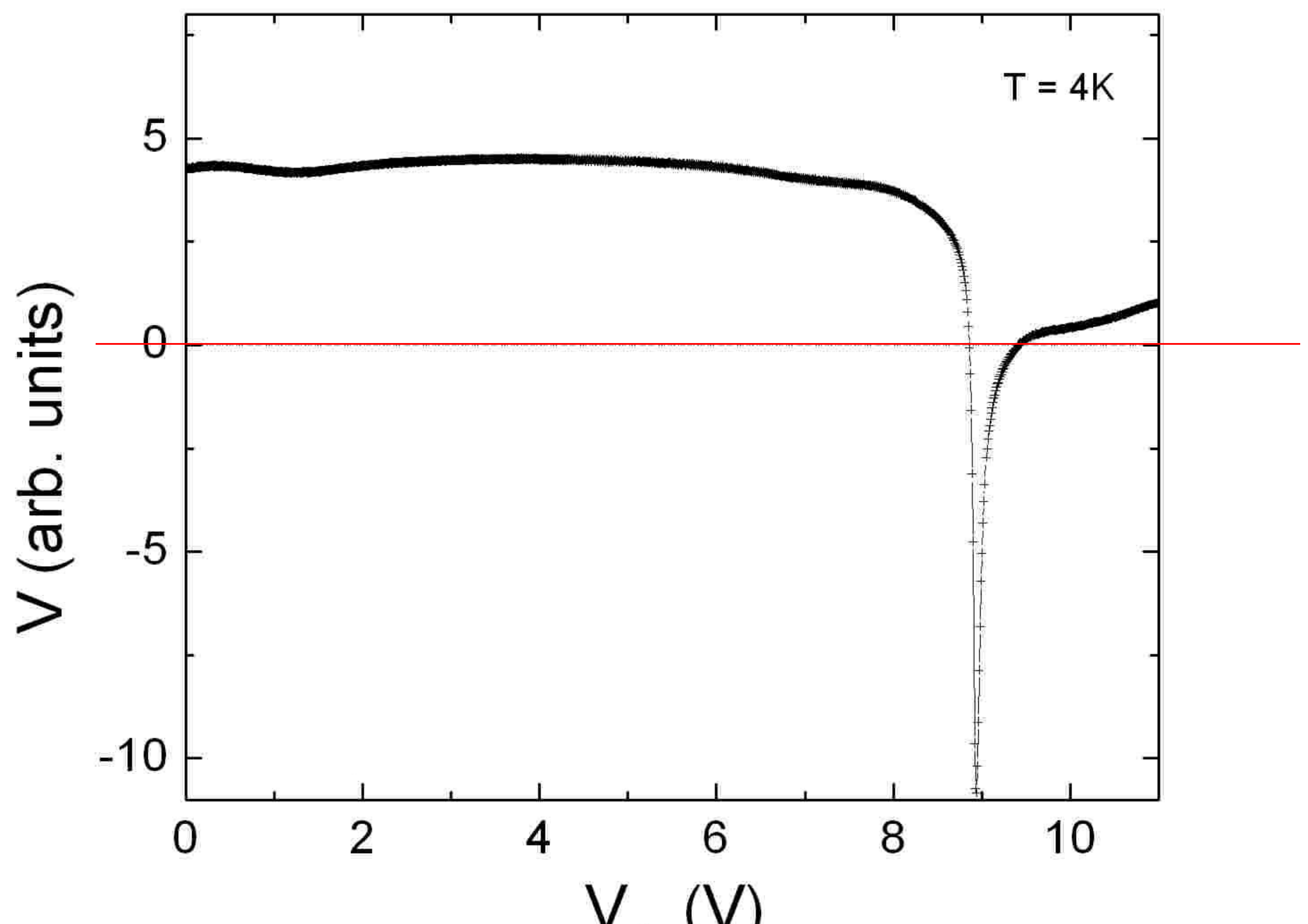


$V_{\text{lock-in}} = R_0/(R_0+r) \times Vac$

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**

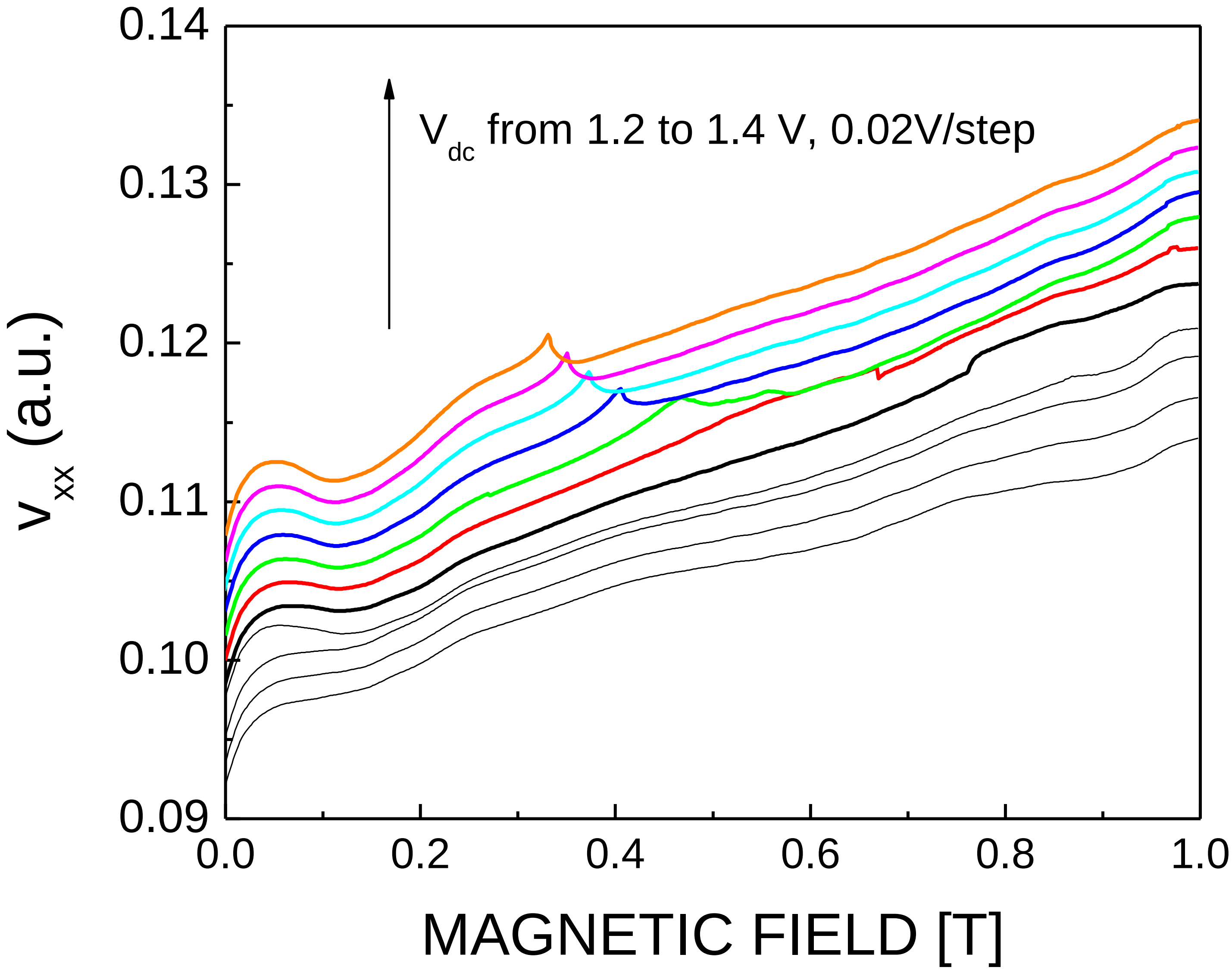
true negative differential conductance



physical origin of NDC ?

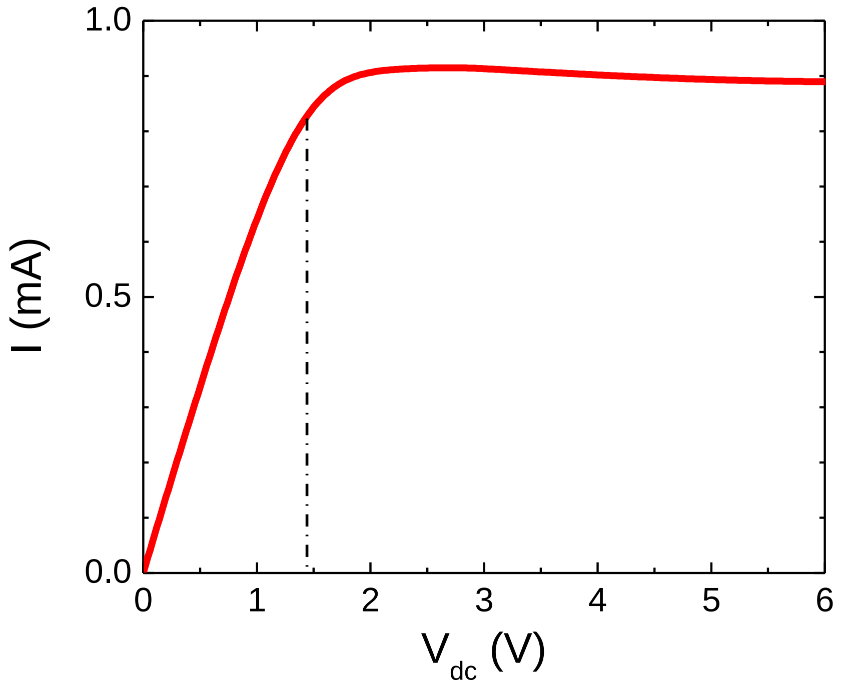
- Bloch oscillation?
- ~~thermal runaway?~~
- ….

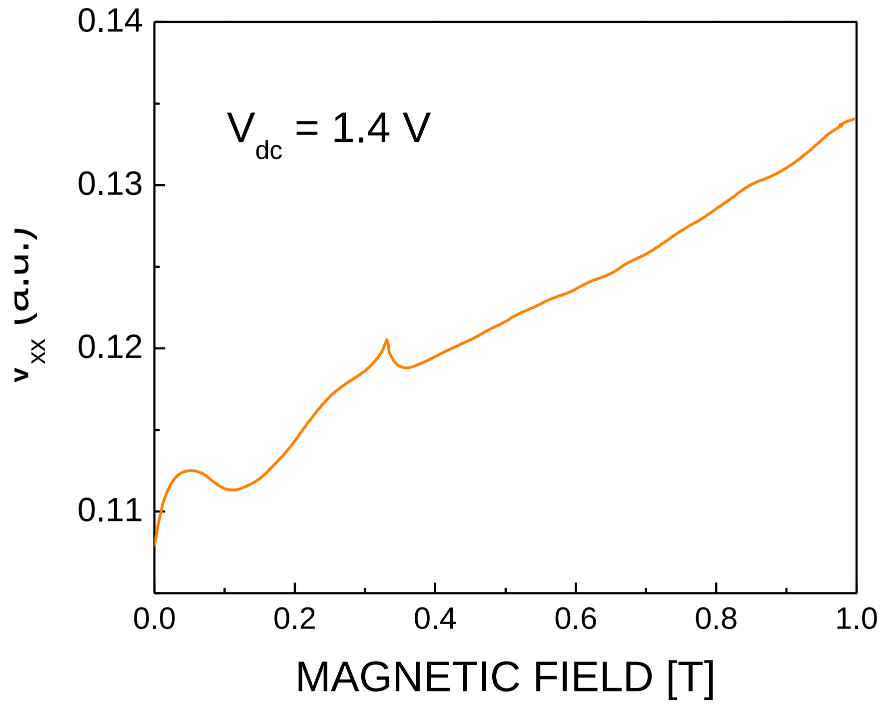
more results on Bloch oscillations



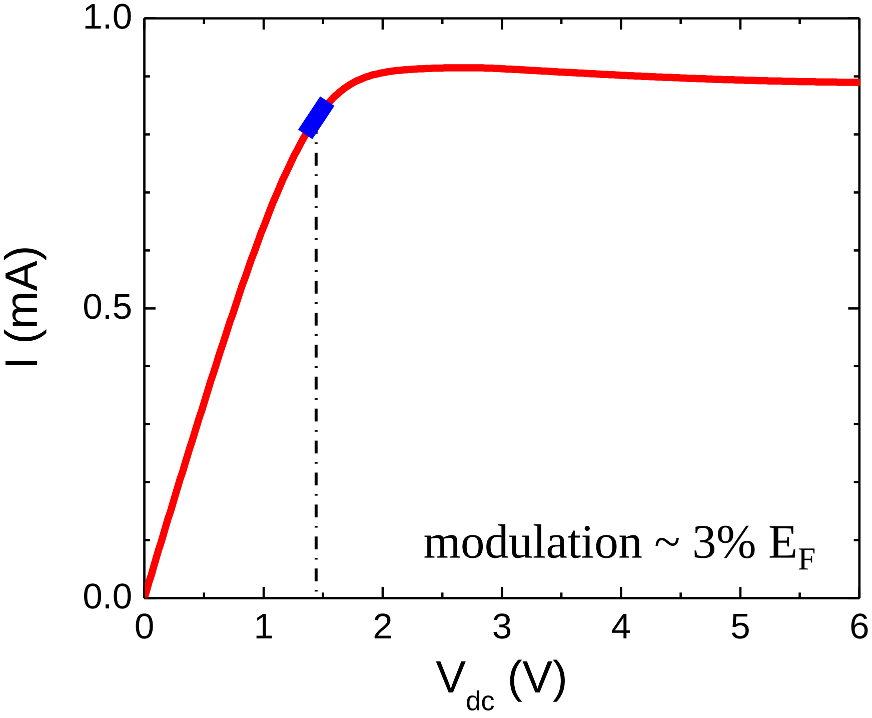
V_{dc} from 1.2 to 1.4 V, 0.02V/step
v_{xx} (a.u.)
MAGNETIC FIELD [T]
0.09
0.10
0.11
0.12
0.13
0.14
0.0
0.2
0.4
0.6
0.8
1.0

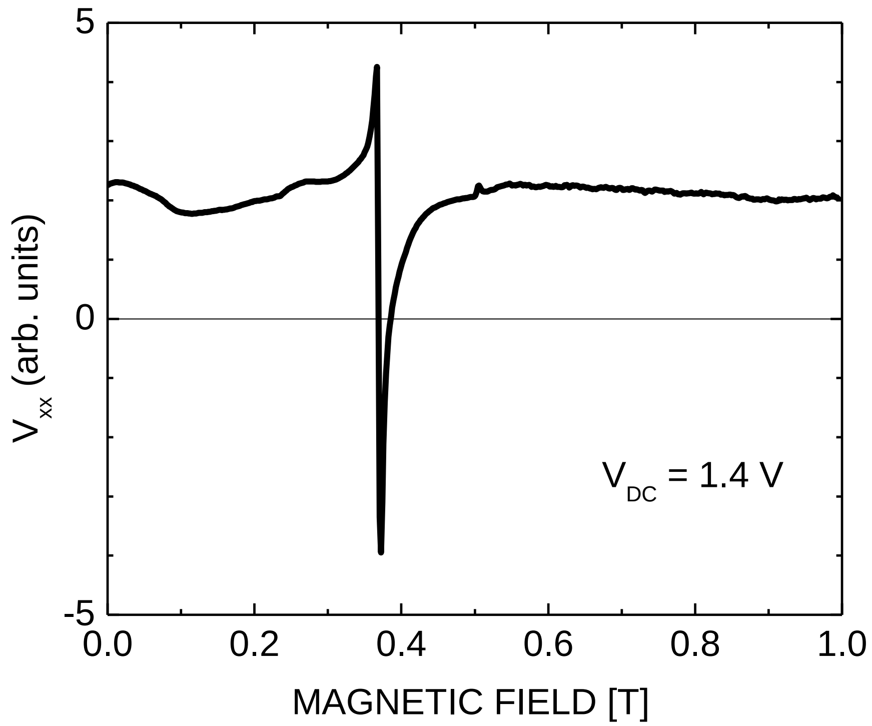
magneto transport at high electric fields

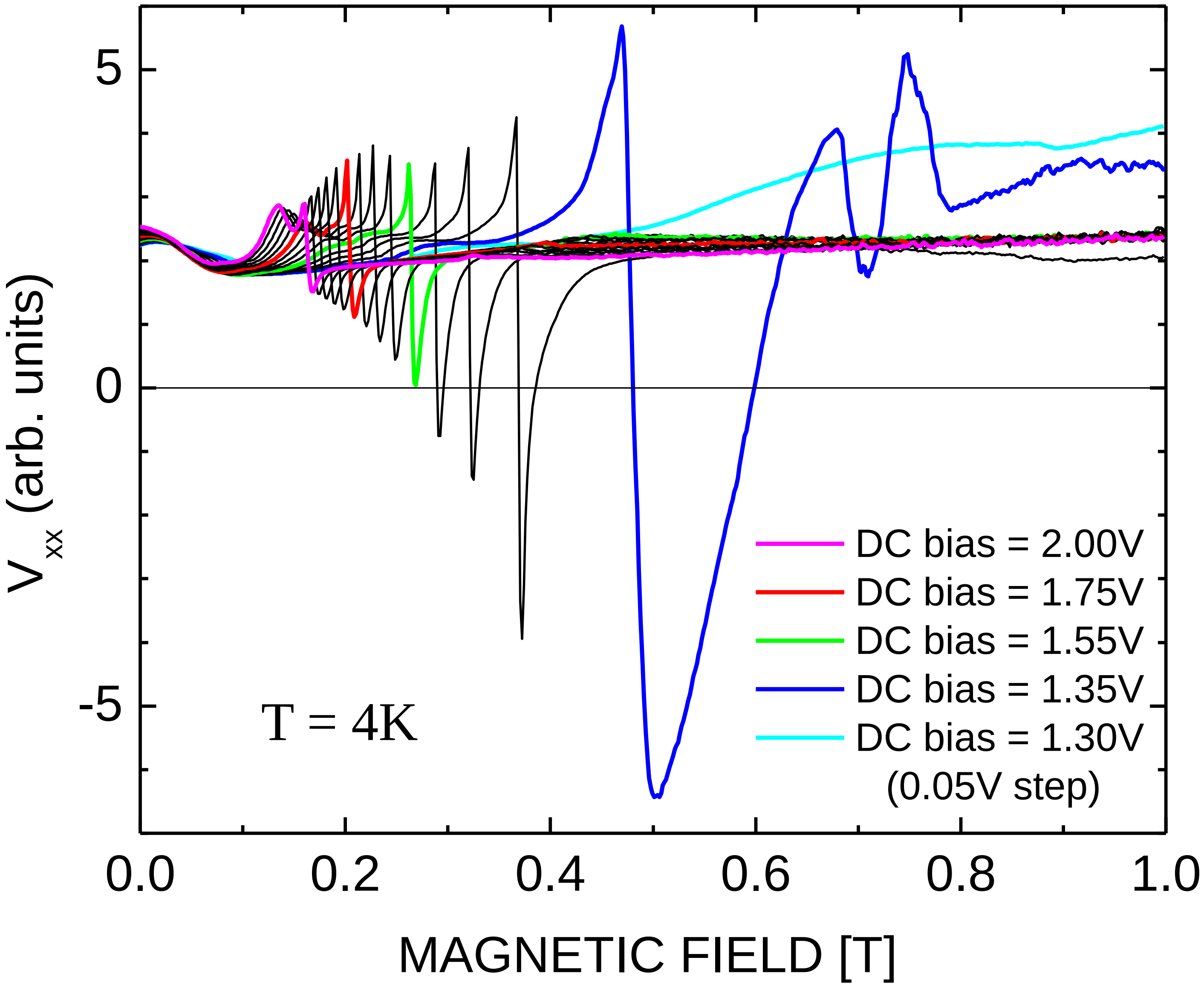




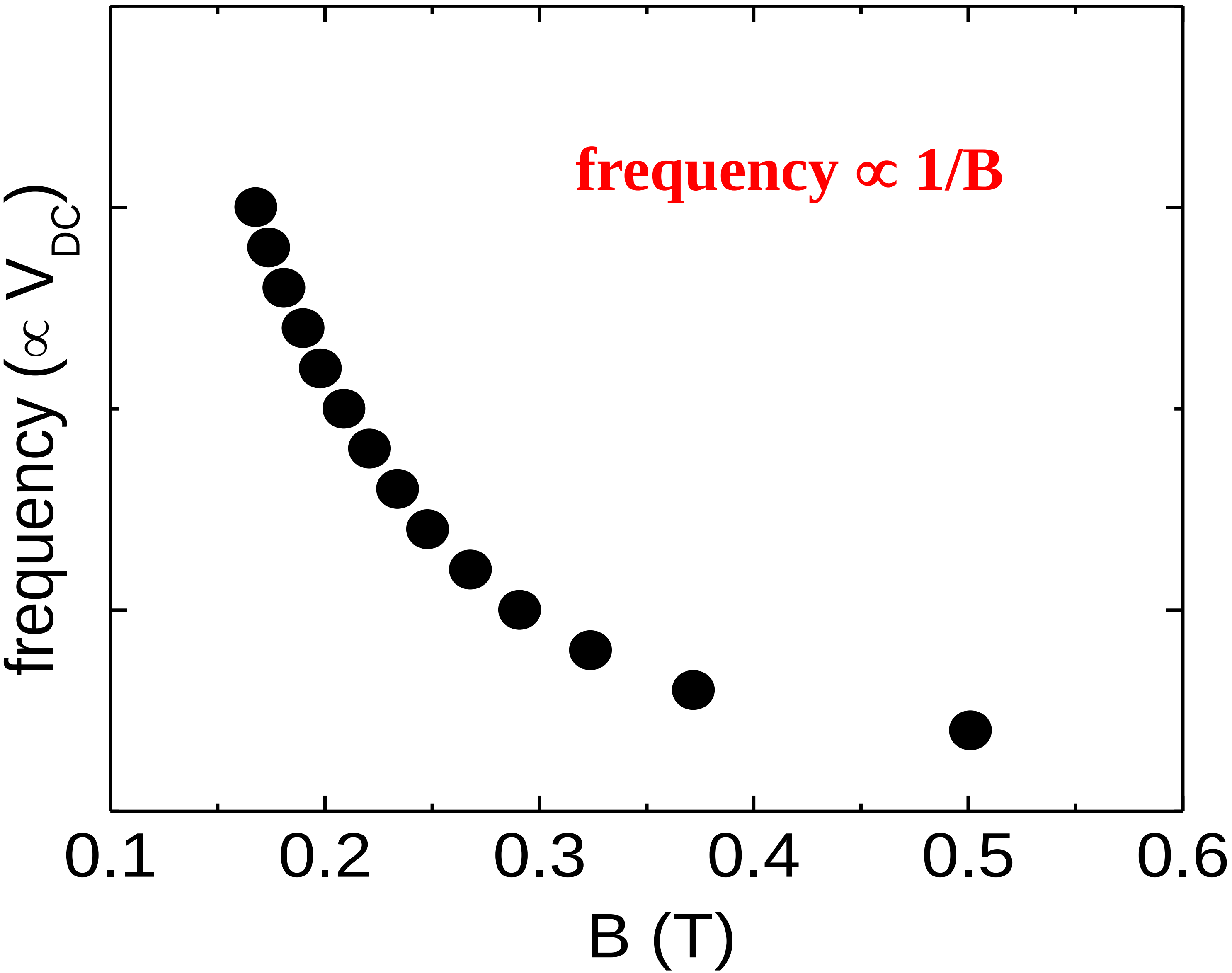
derivative measurement





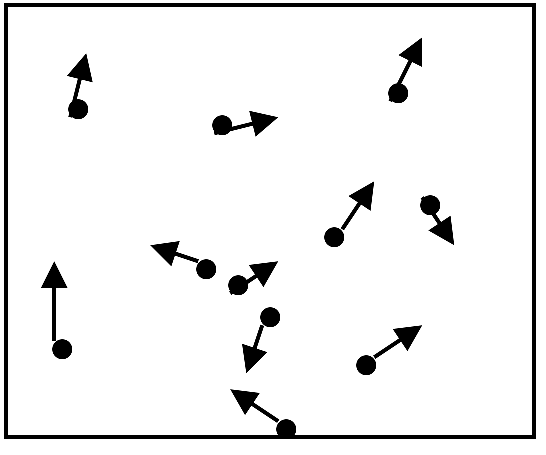


5
0
-5
0.0
0.2
0.4
0.6
0.8
1.0
V_{xx} (arb. units)
MAGNETIC FIELD [T]
T = 4K
DC bias = 2.00V
DC bias = 1.75V
DC bias = 1.55V
DC bias = 1.35V
DC bias = 1.30V
(0.05V step)

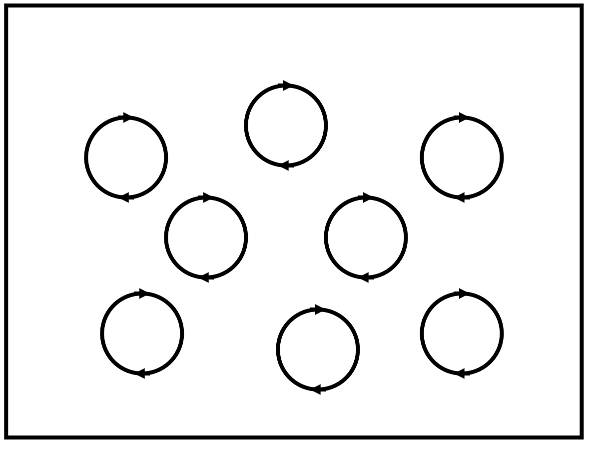

frequency ∝ 1/B
frequency (∝ V_{DC})
0.1
0.2
0.3
0.4
0.5
0.6
B (T)

Cyclotron motion

$B = 0$

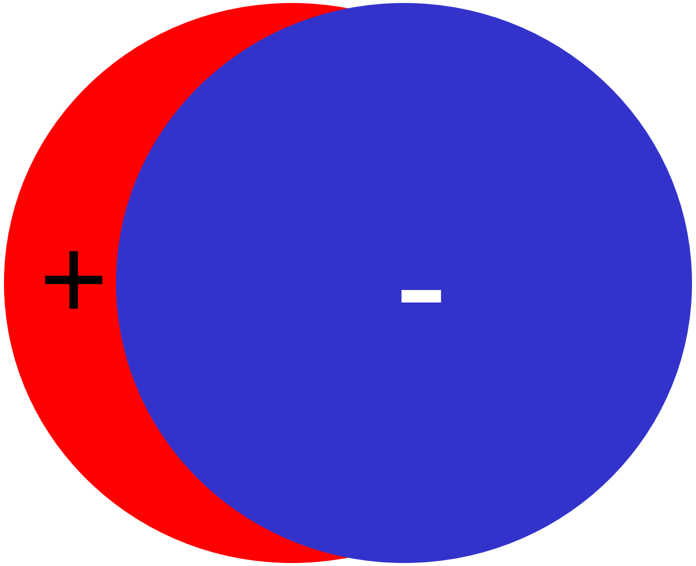


$B \neq 0$



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

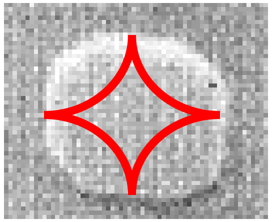
Plasmon oscillations



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

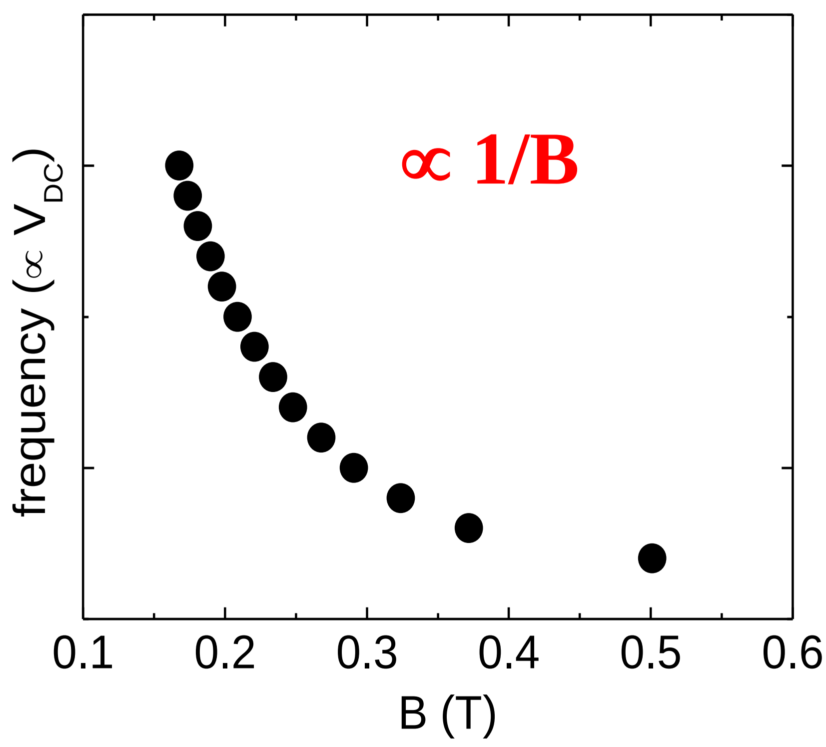
in an infinitely large sample, ω_0 is very small, no coupling between the cyclotron mode and plasmon mode.

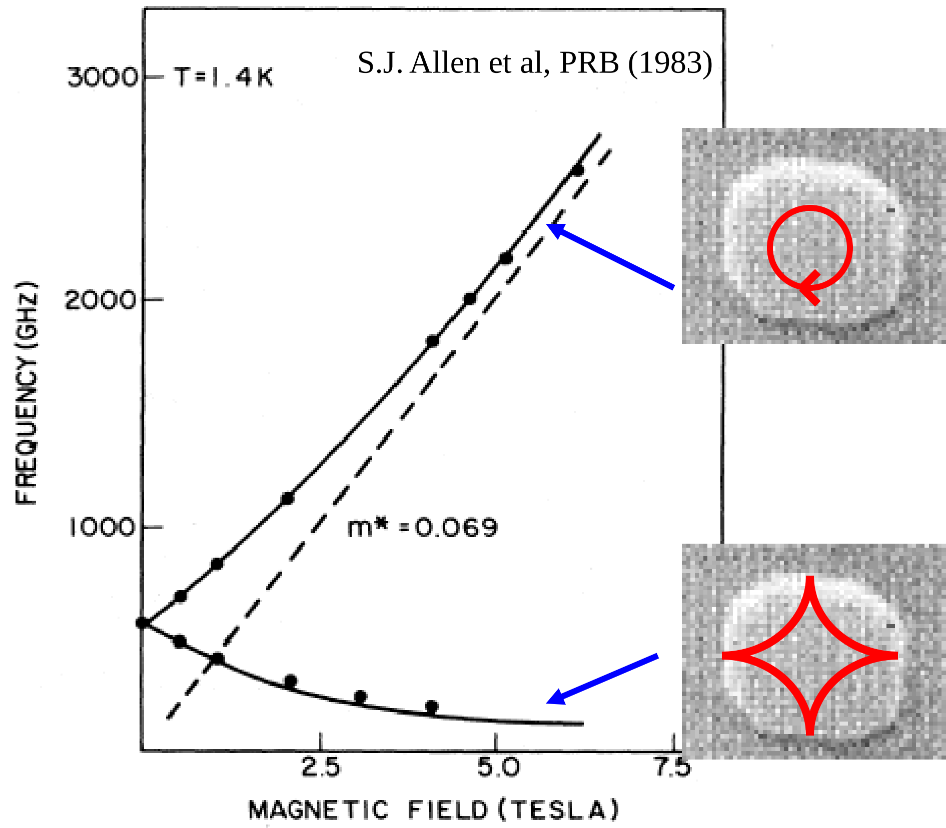
In a sample of finite size, ~ μm, there is strong coupling between the two. This results in a new resonance mode, edge magnetoplasmon mode.



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

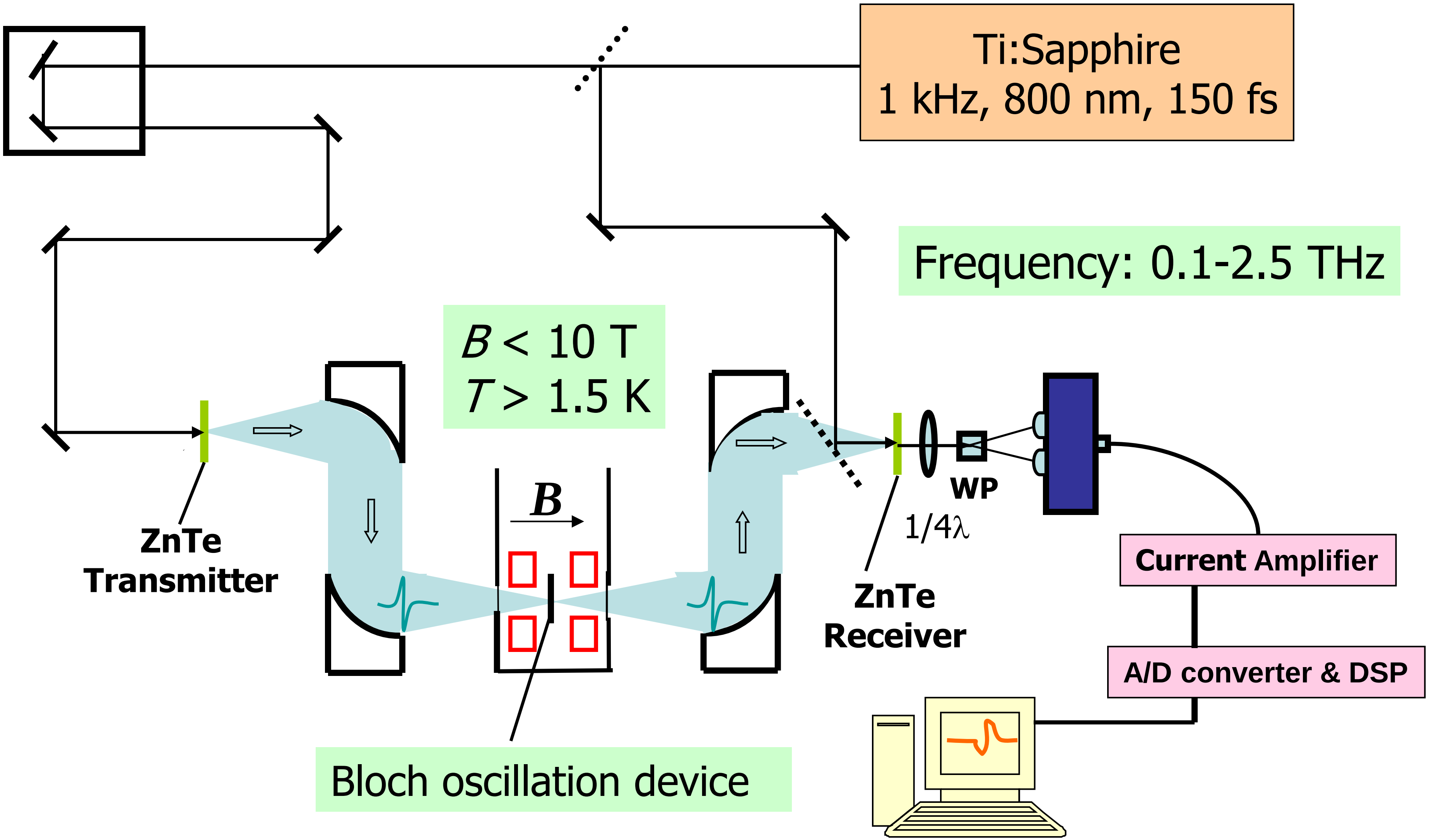
edge magnetoplasmon resonance





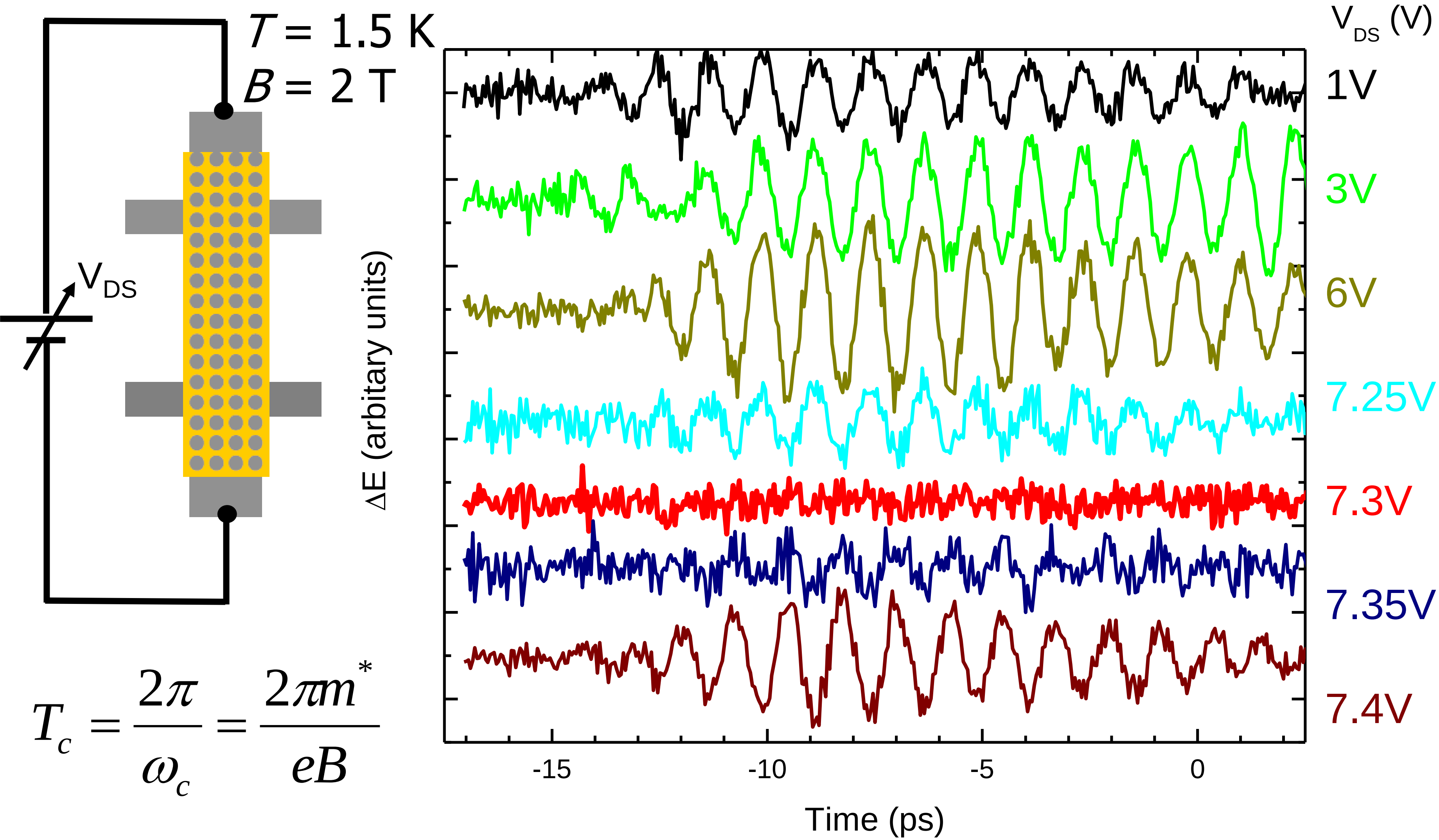
$\omega = -\omega_c/2 + [(\omega_c/2)^2 + \omega_0^2]^{1/2}$ ∝ **1/B** at high B fields

time-domain THz magneto-spectroscopy

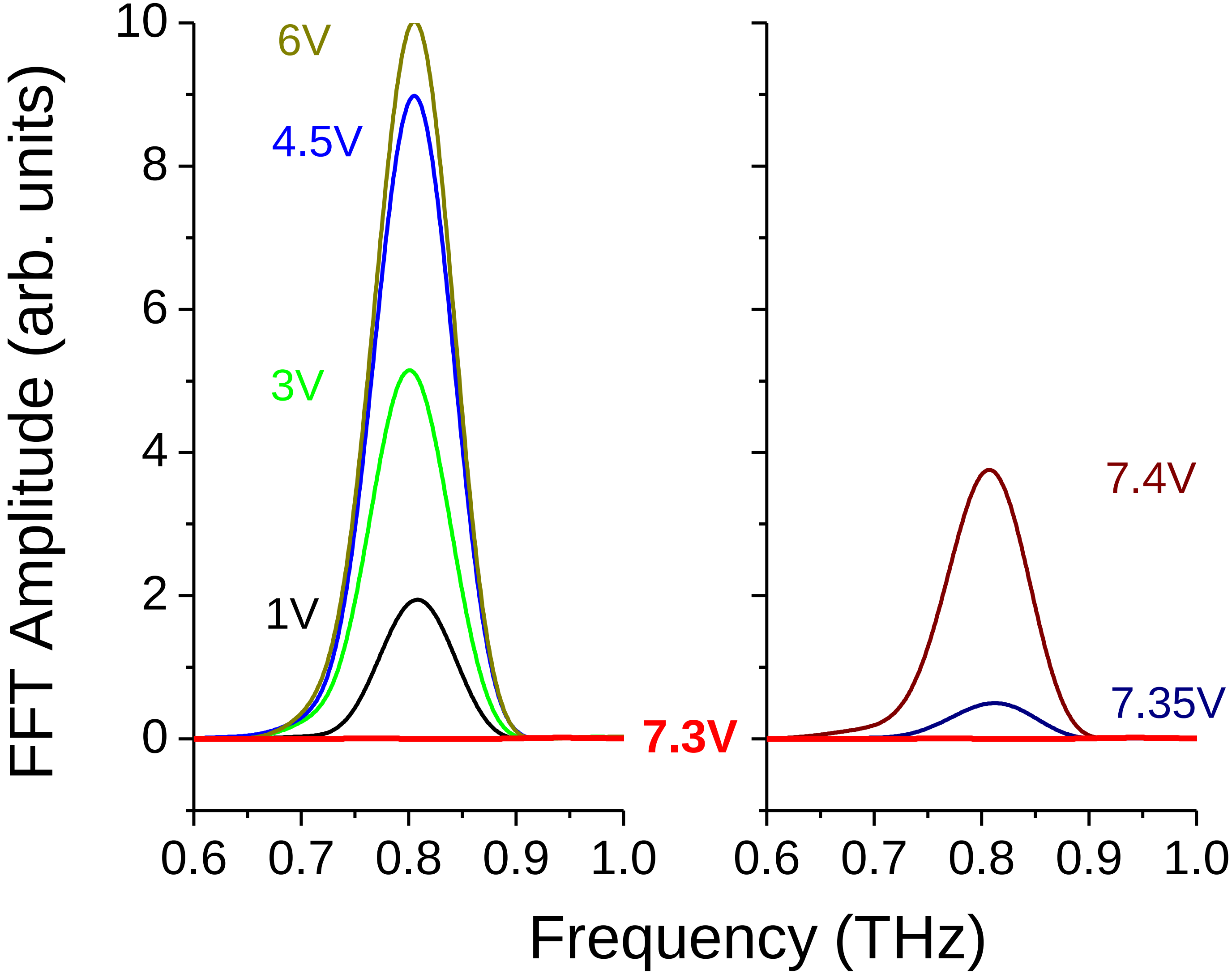


in collaboration with Jun Kono at Rice Univ.

coherent cyclotron resonance in Bloch oscillator

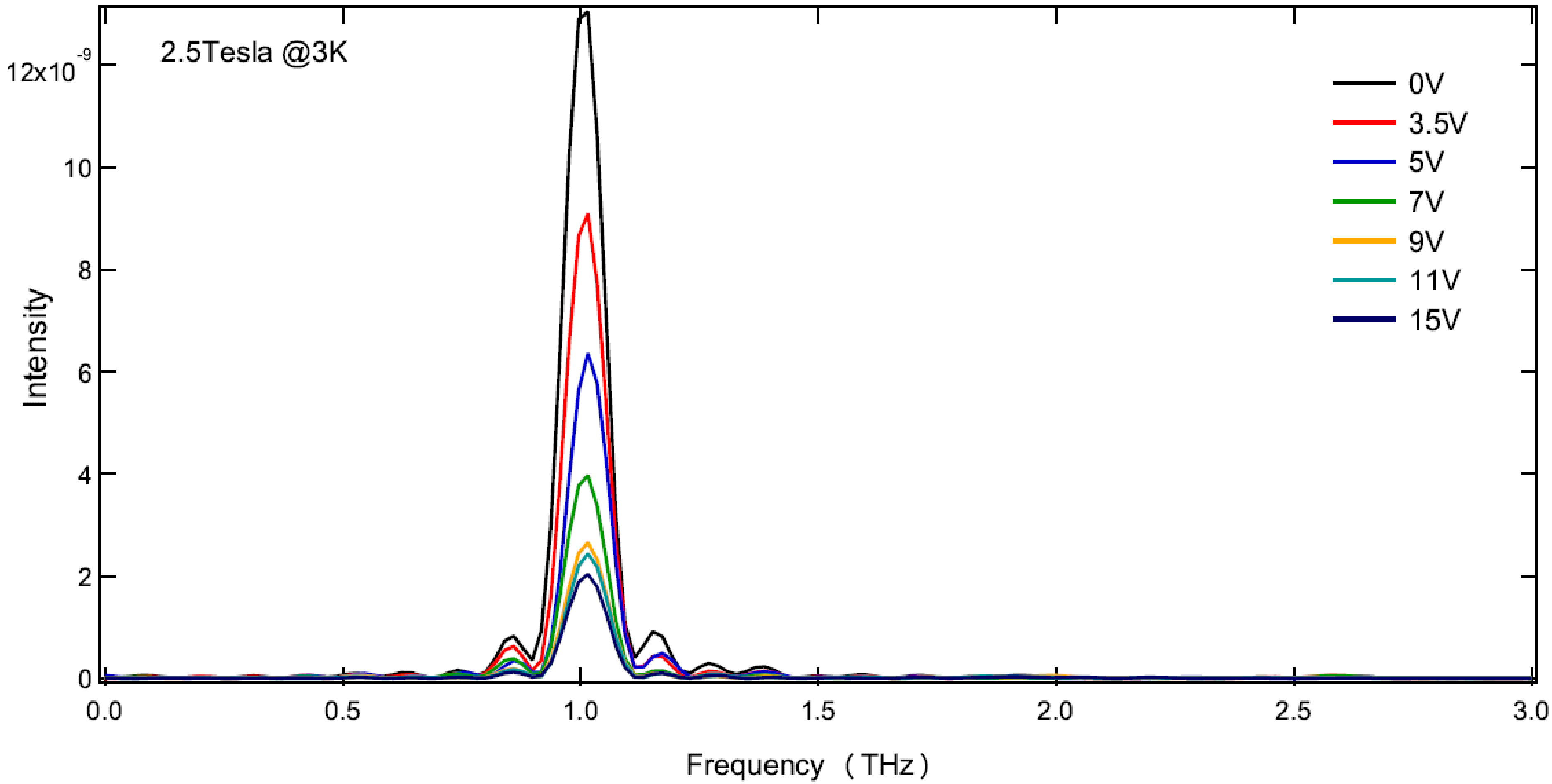


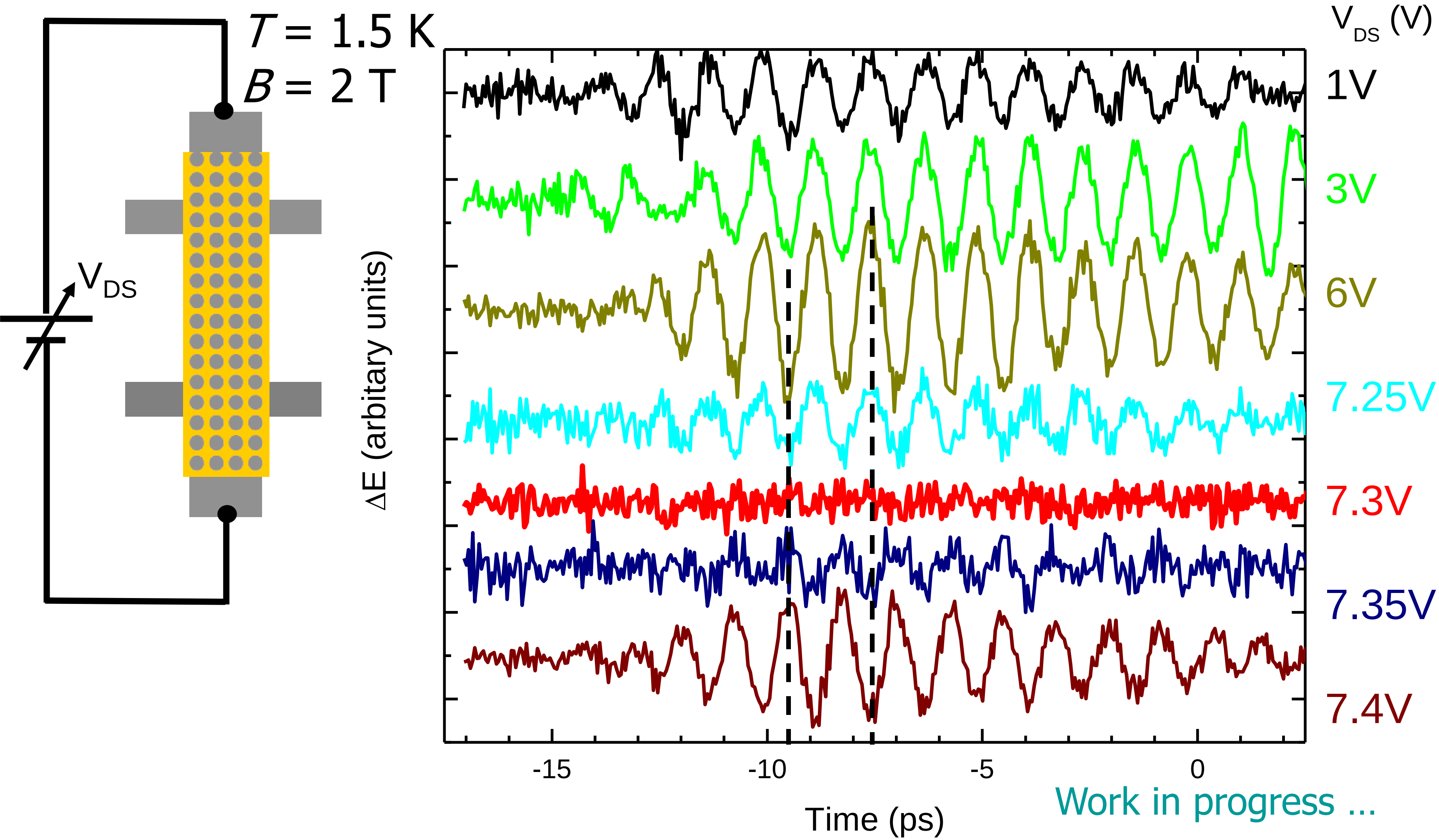
$$T_c = \frac{2\pi}{\omega_c} = \frac{2\pi m^*}{eB}$$



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

2D sample without patterning





E-Field-Induced THz Phase Flip!

Thank you!