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Quantum Transport Properties in Two-Dimensional Quantum Dot Superlattices

Wei Pan

Sandia National Laboratories

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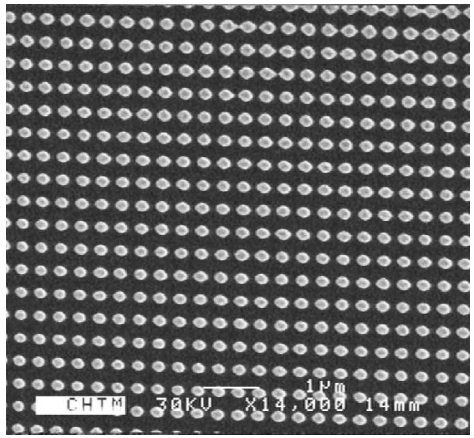
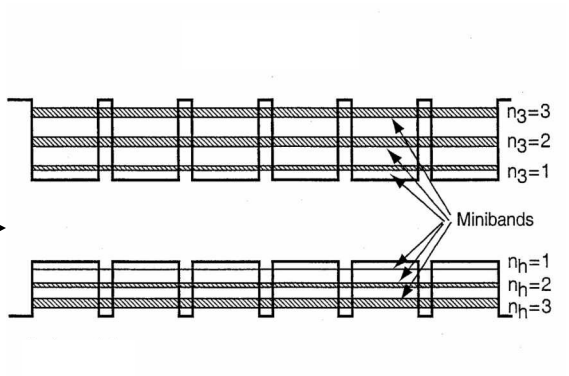
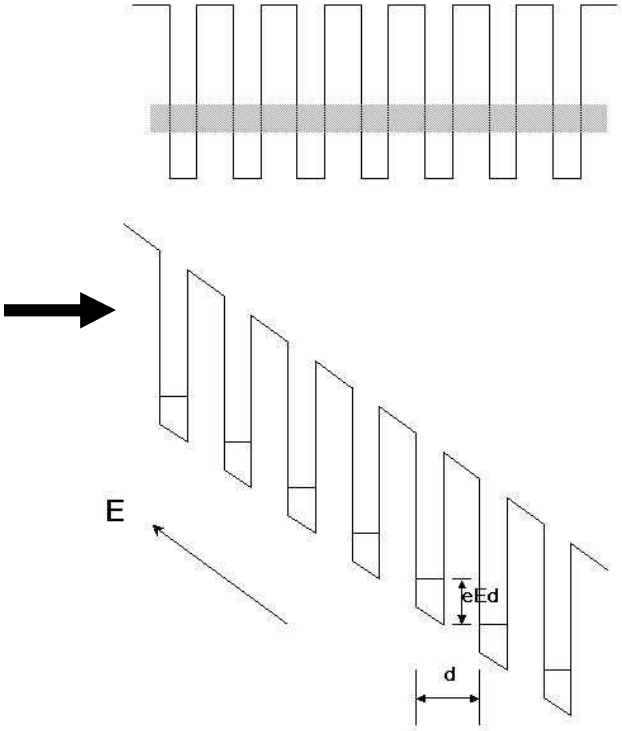
Outline

- Motivation
- Sample fabrication and characterization
- ν=1 quantum Hall state
- Evidence of Bloch oscillation:
  - ✓ I-V measurement
  - ✓ Edge magnetoplasmon resonance like behavior
- Summary

Motivation – Bloch oscillation in 2D quantum dot superlattice (QDSL)





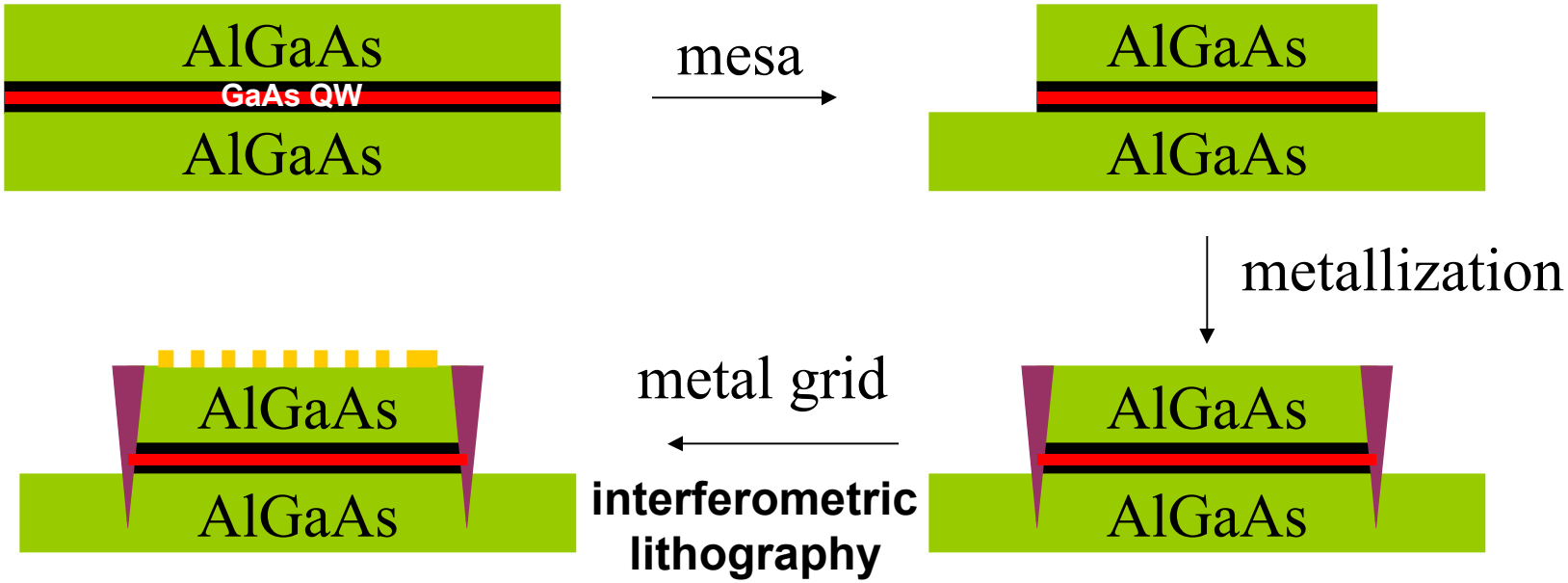


2D QDSL

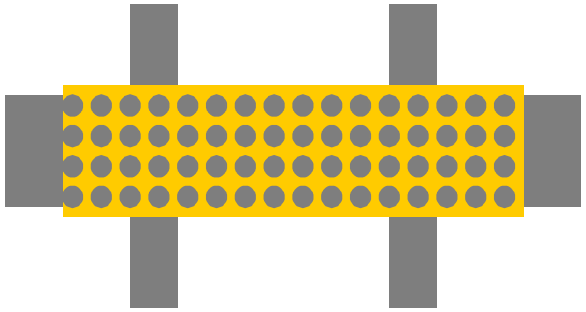
Formation of mini-bands

Wannier-Stark ladders

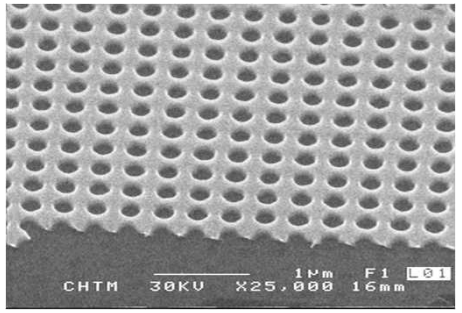
Sample fabrication



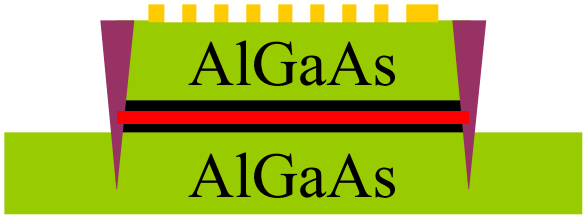
Top view

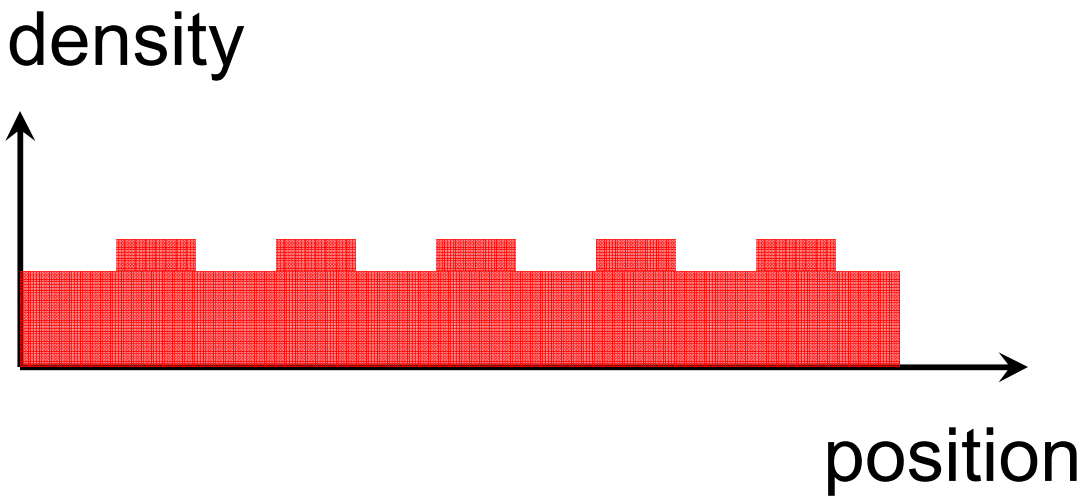


SEM picture

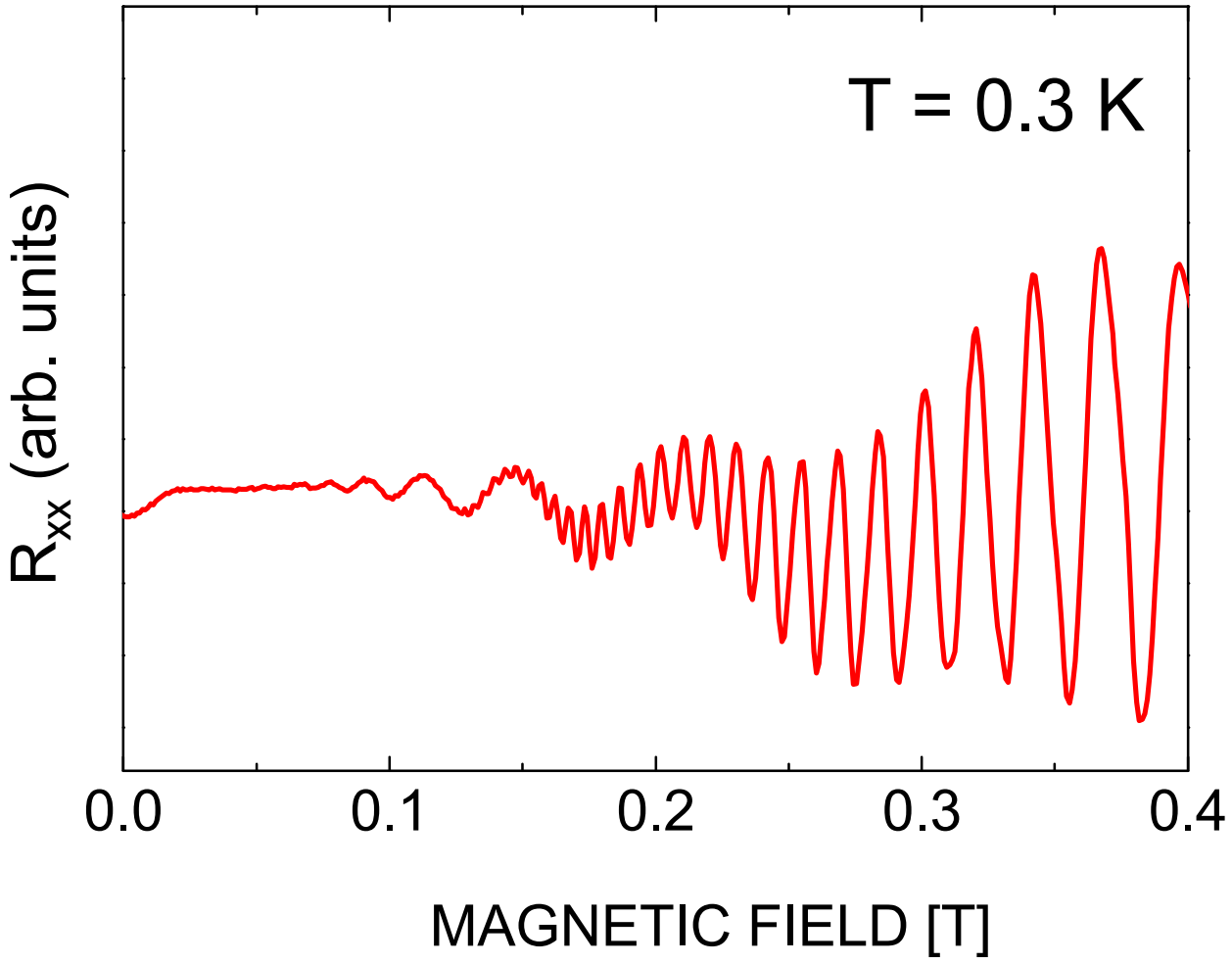


Periodic density modulation

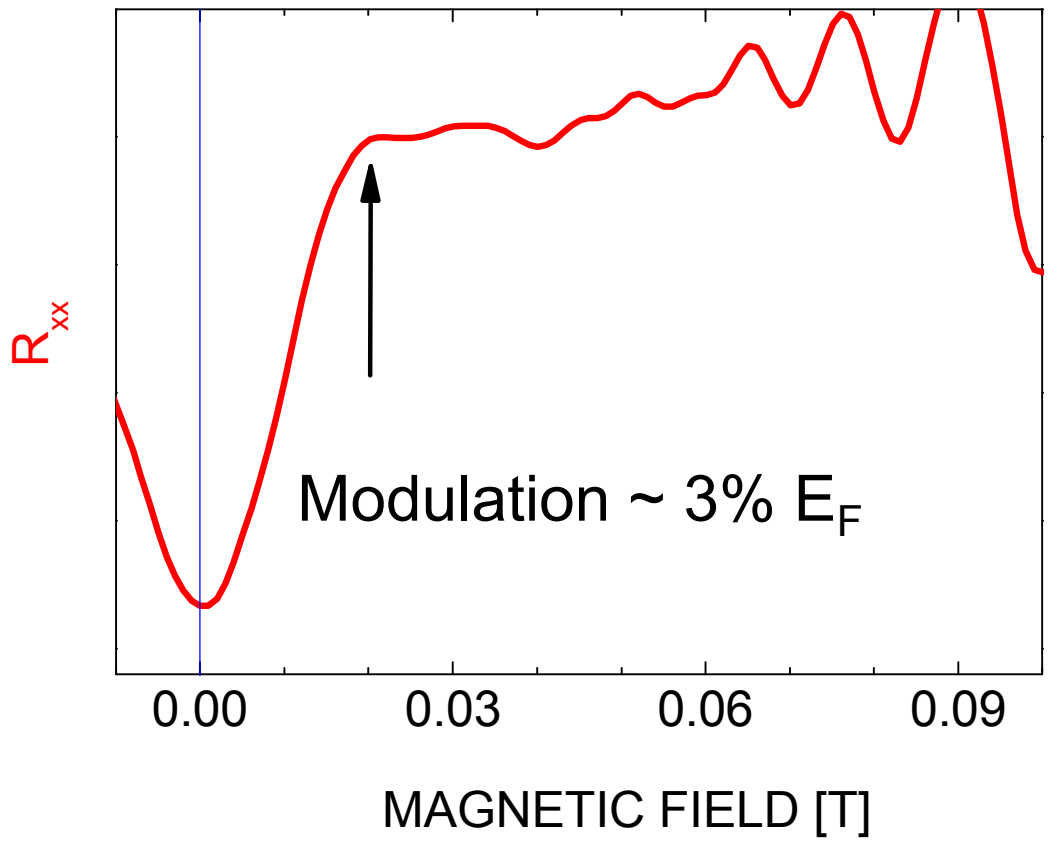




Sample characterization – magneto-transport

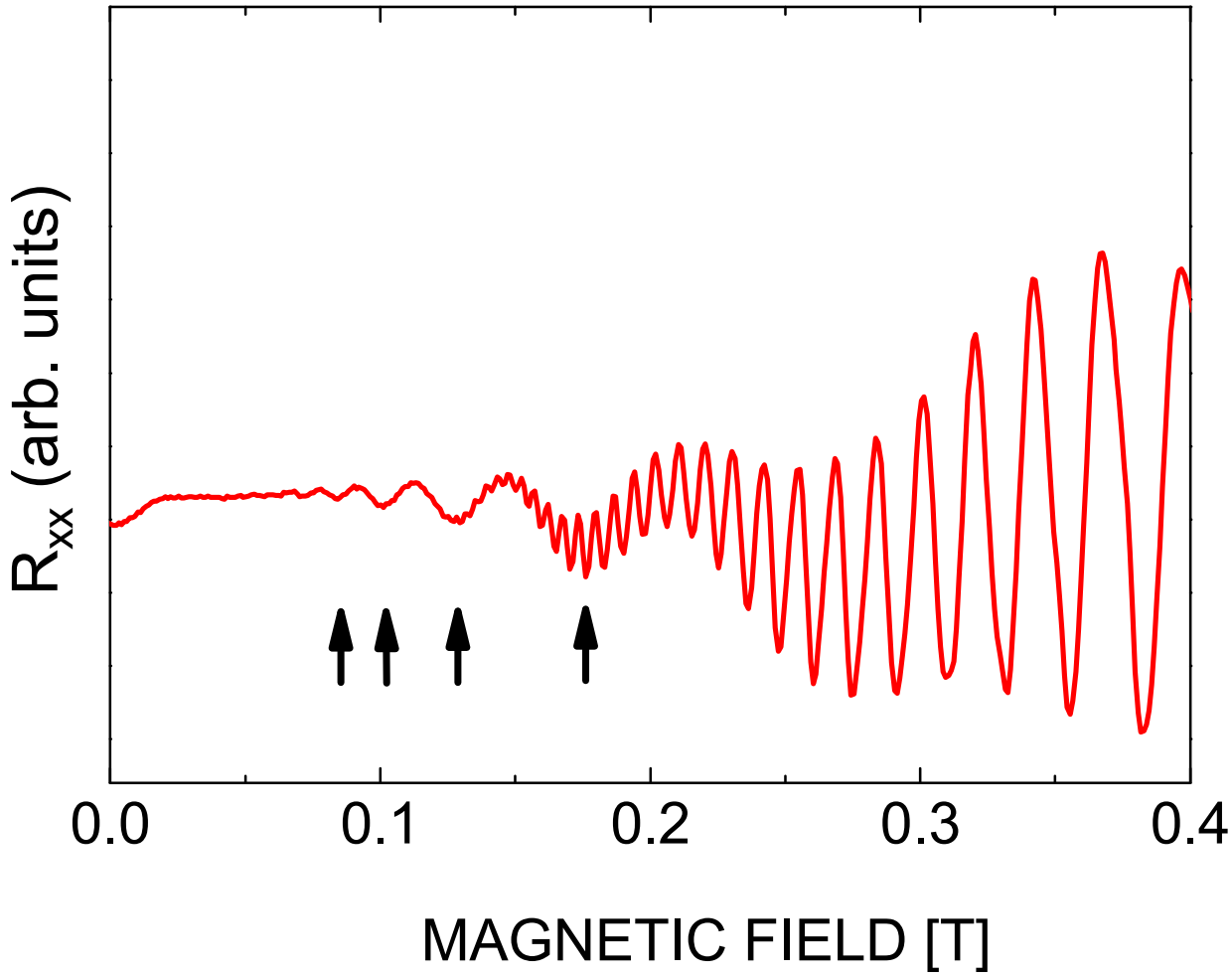


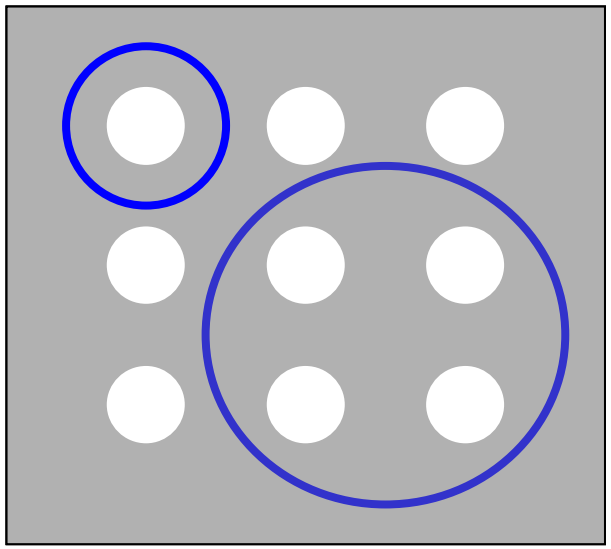
Positive magneto-resistance around B = 0



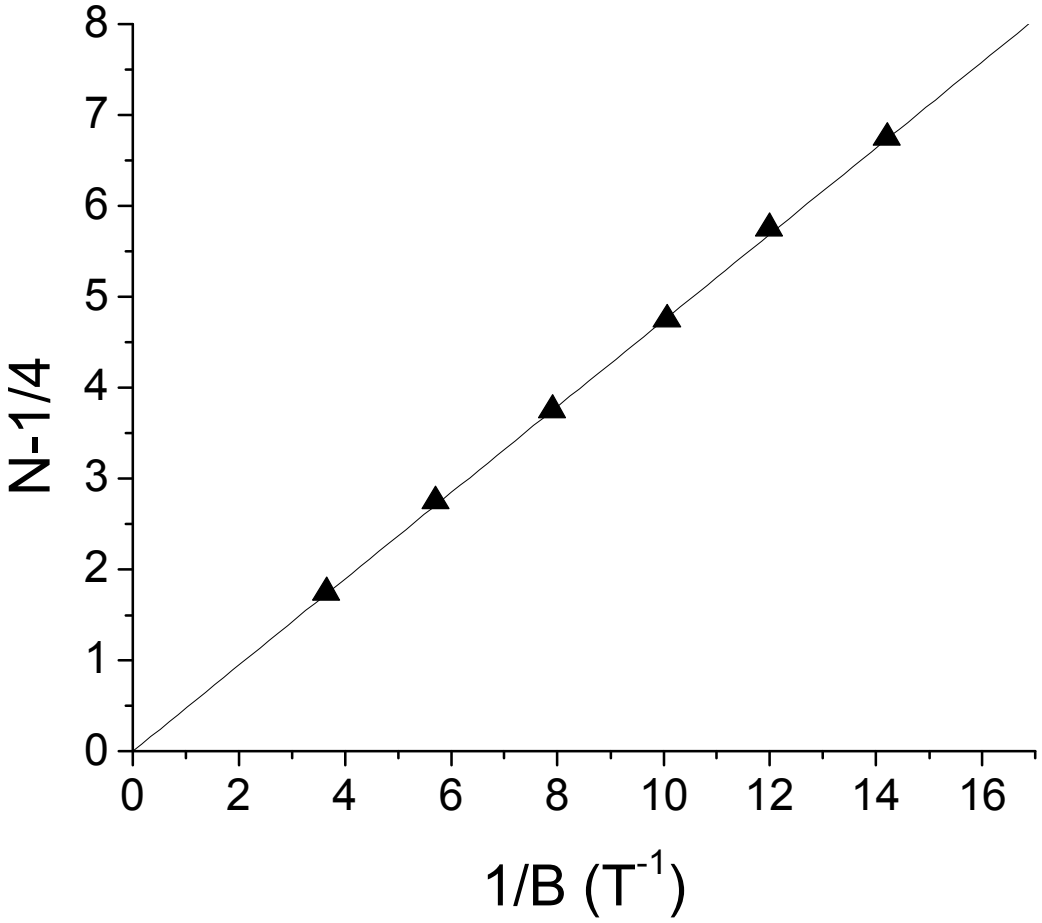
Beton, et al, PRB 42, 9229 (1990)

Commensurability oscillation





Weiss et al, PRL 66, 2790 (1991)



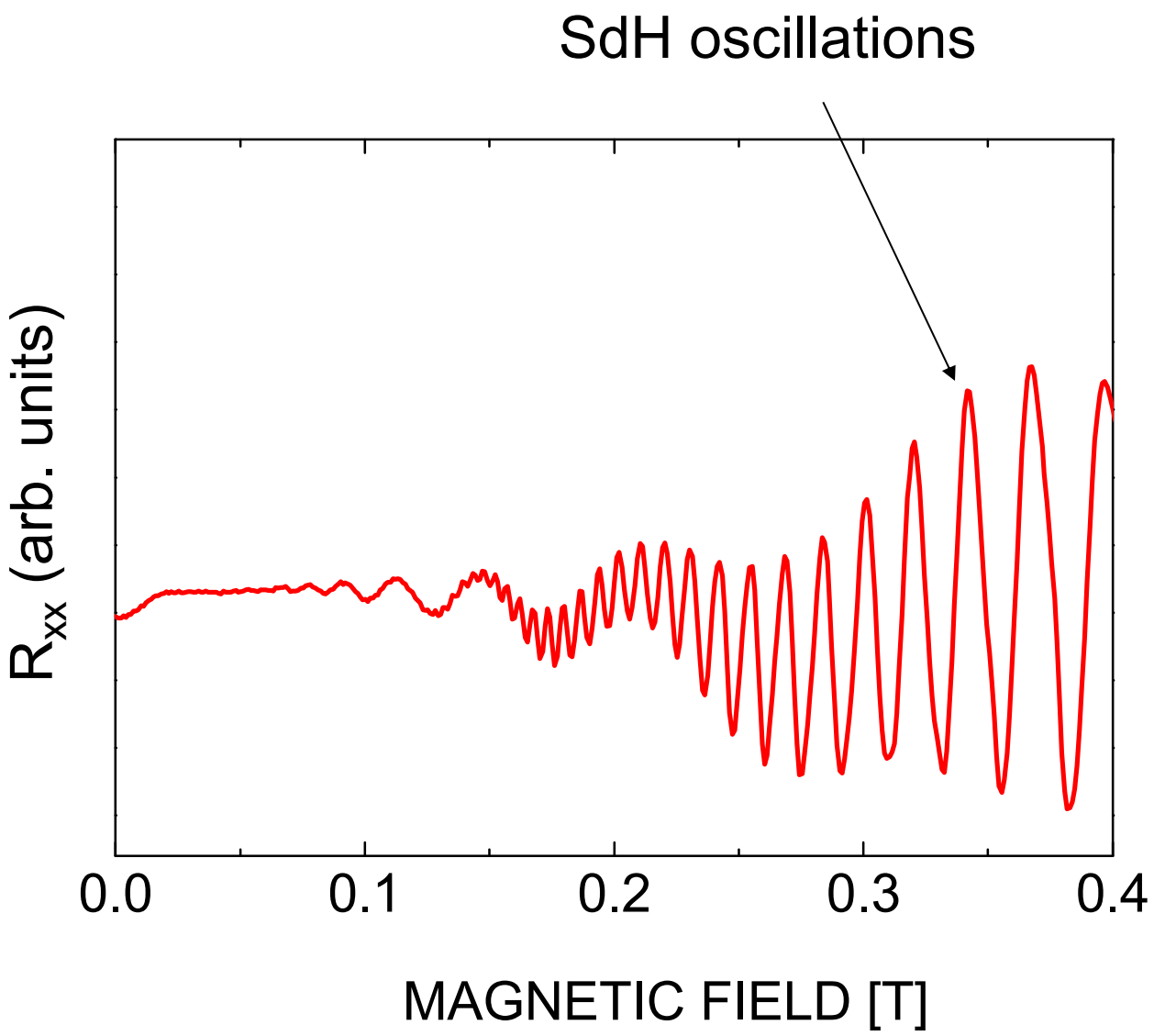
$2R_c/d = N\text{-}1/4$

or

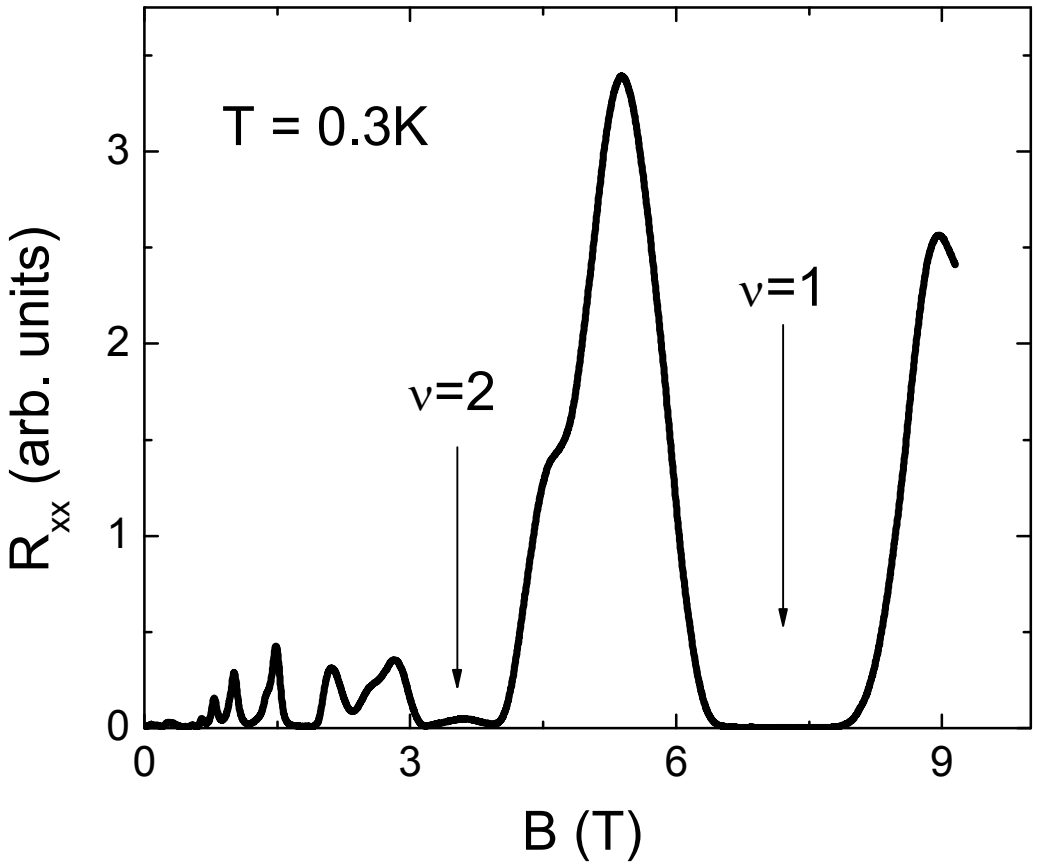
$N\text{-}1/4 = (2\hbar k_F/ed)\times 1/B$

From slope,
d ~ 340 nm

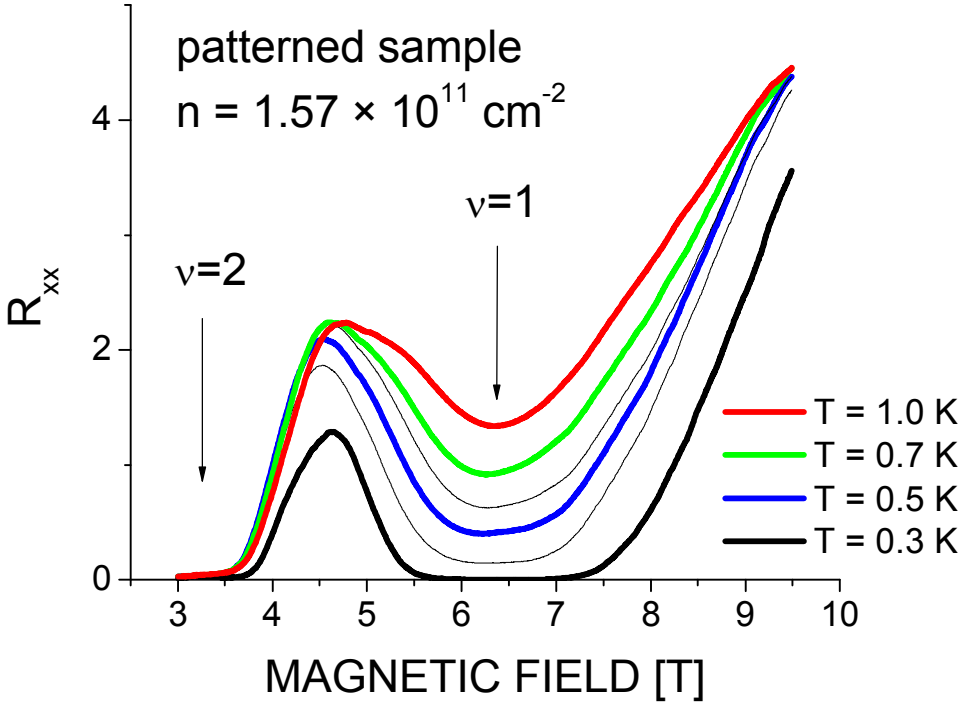
Weiss et al, PRL 66, 2790 (1991)

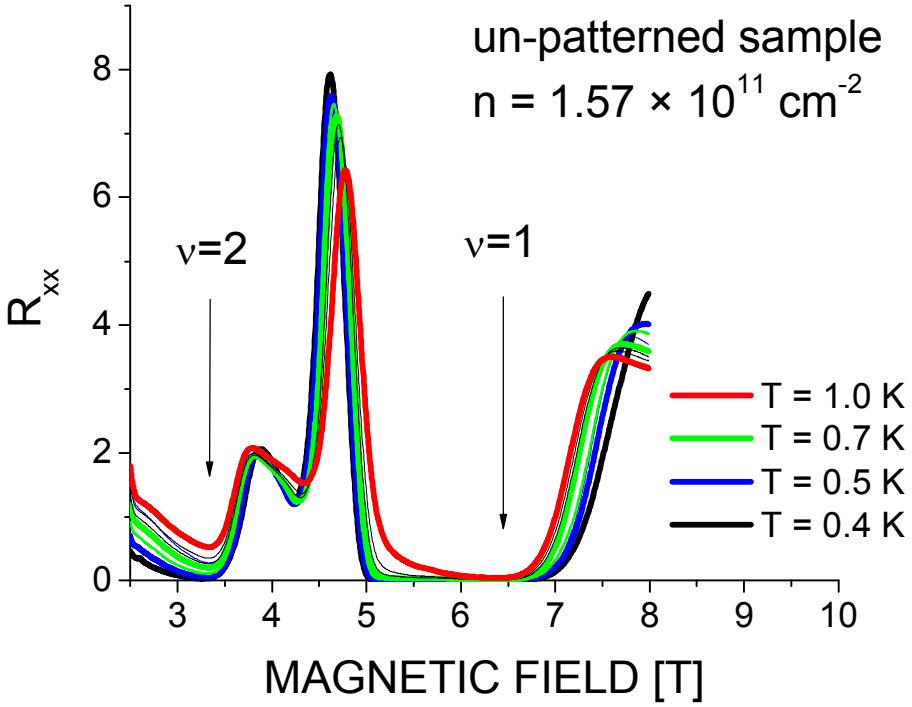

SdH oscillations
R_{xx} (arb. units)
0.0
0.1
0.2
0.3
0.4
MAGNETIC FIELD [T]

Well developed integer quantum Hall states



Weakened ν=1 Quantum Hall state in QDSL

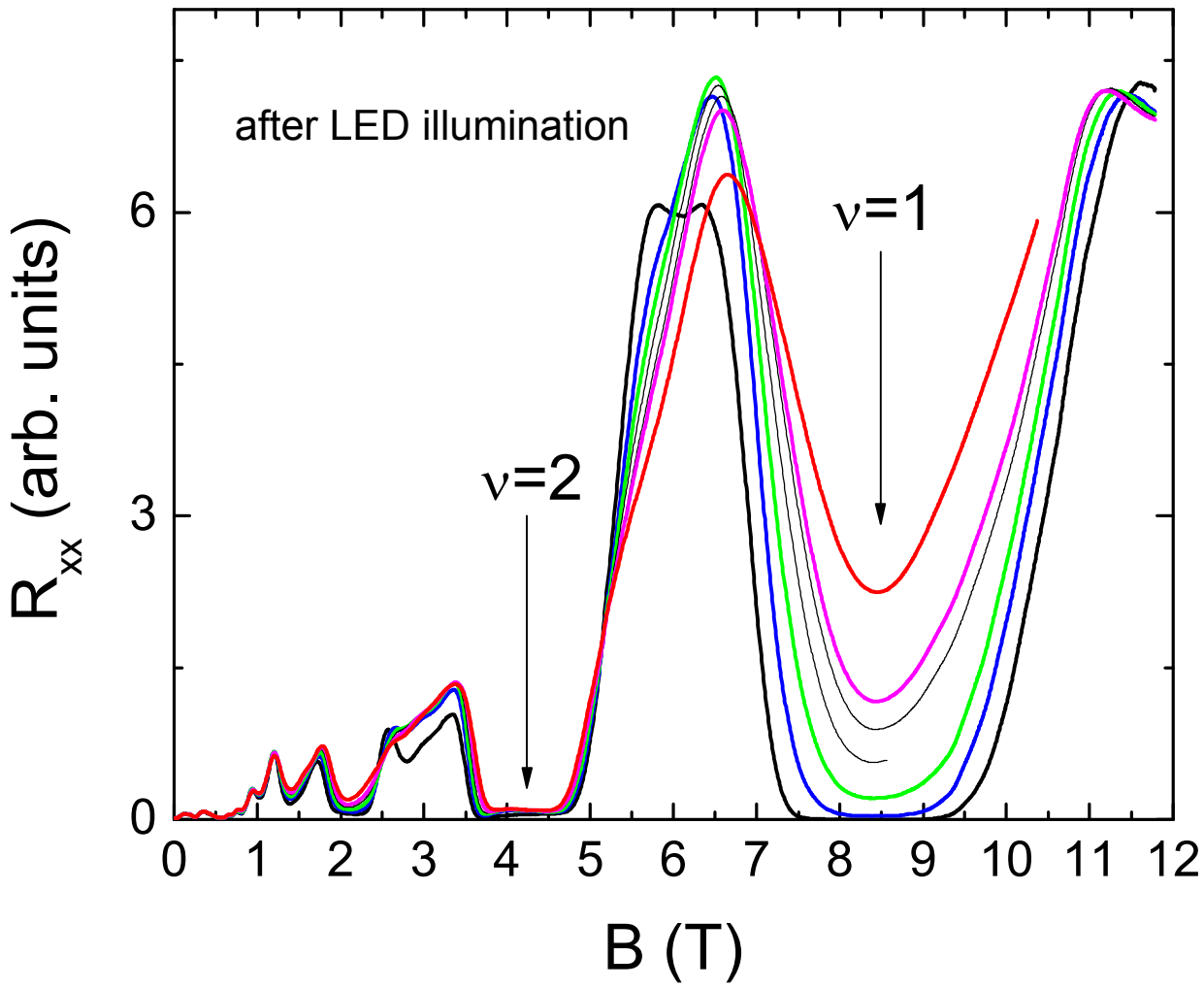




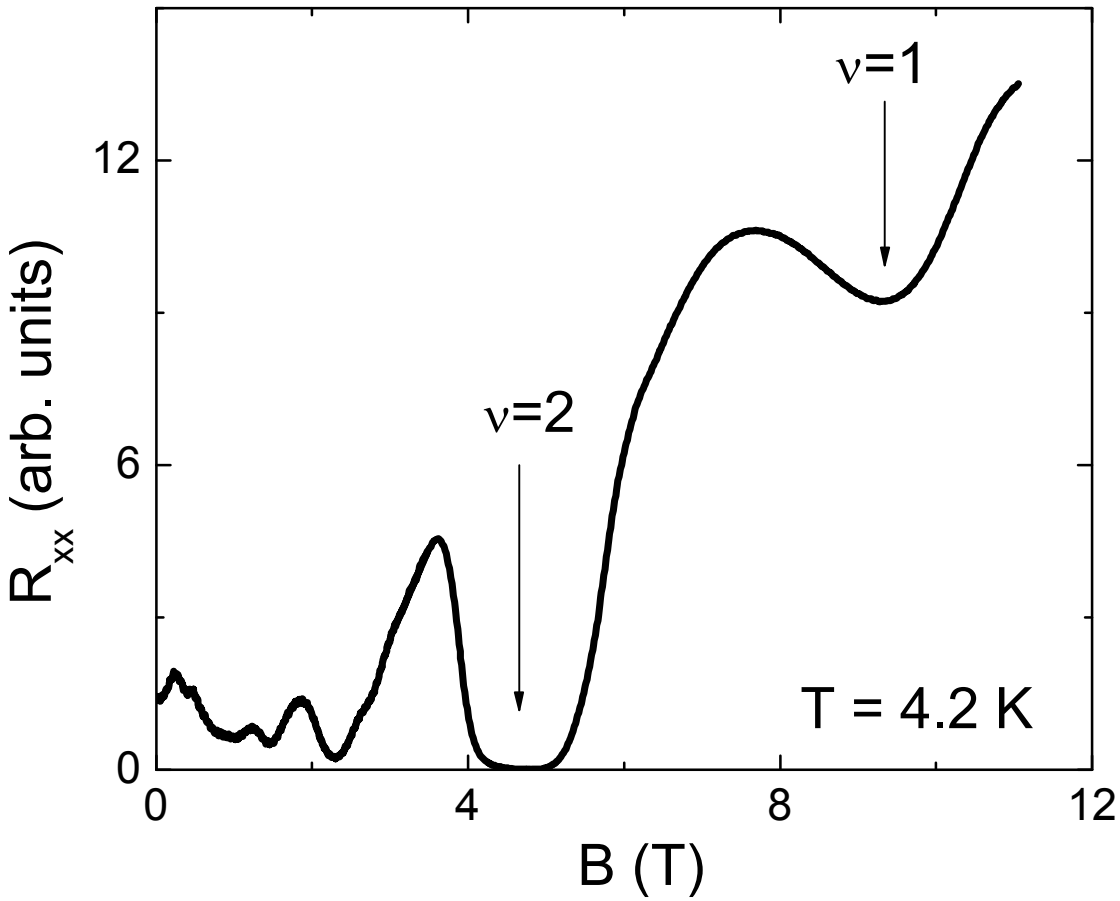
Energy gap at ν=1 is ~ 3K

Energy gap at ν=1 is ~ 20K

Not a density effect



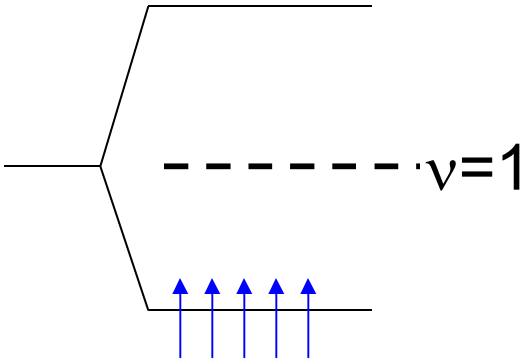
not a screening effect

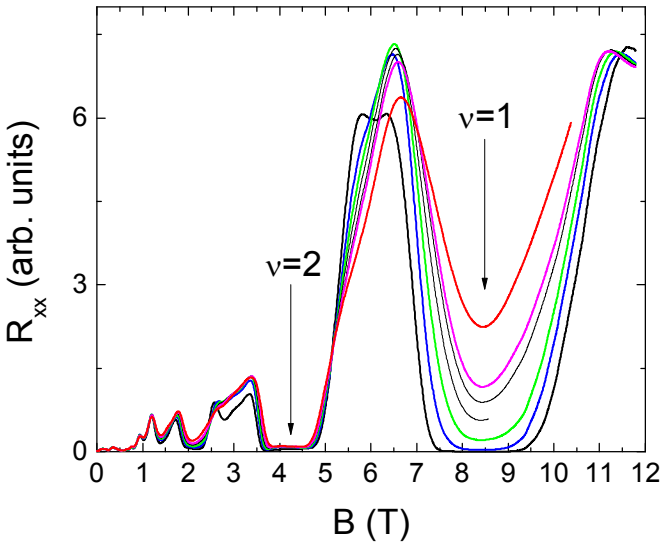


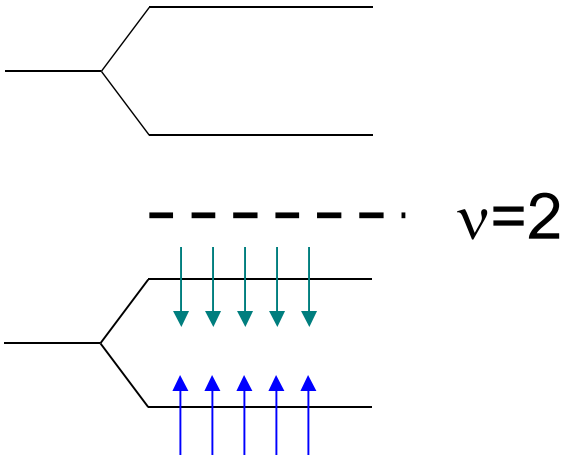
Sample from the same wafer, no gate, true anti-dot array

Possible origins:

- disorder effect?
- density inhomogeneity?
- **spin effect?**



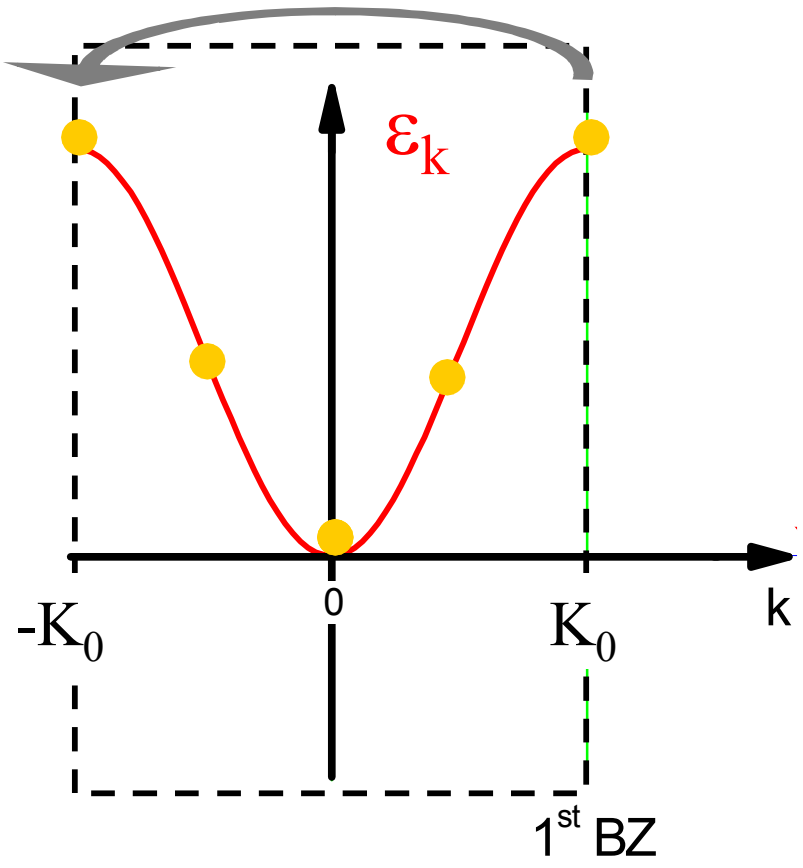




Evidence of Bloch Oscillations

What's Bloch oscillation?

Bloch, Z. Phys. 1928



$K_0 = \pi/a$

Under a DC electric field E

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

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

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

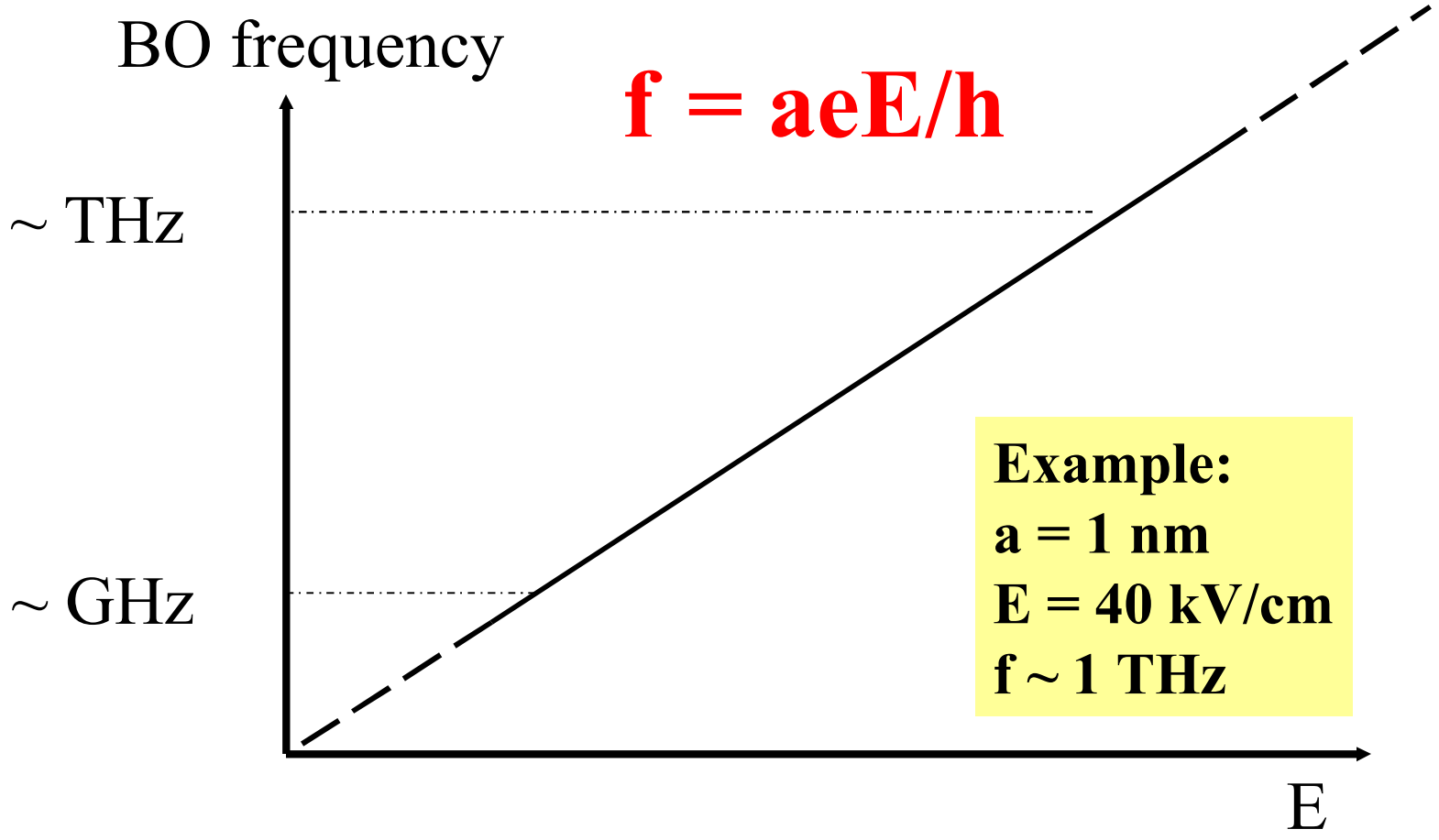
$$\mathbf{r \sim \cos(aeEt/\hbar) = \cos(2\pi ft)}$$

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

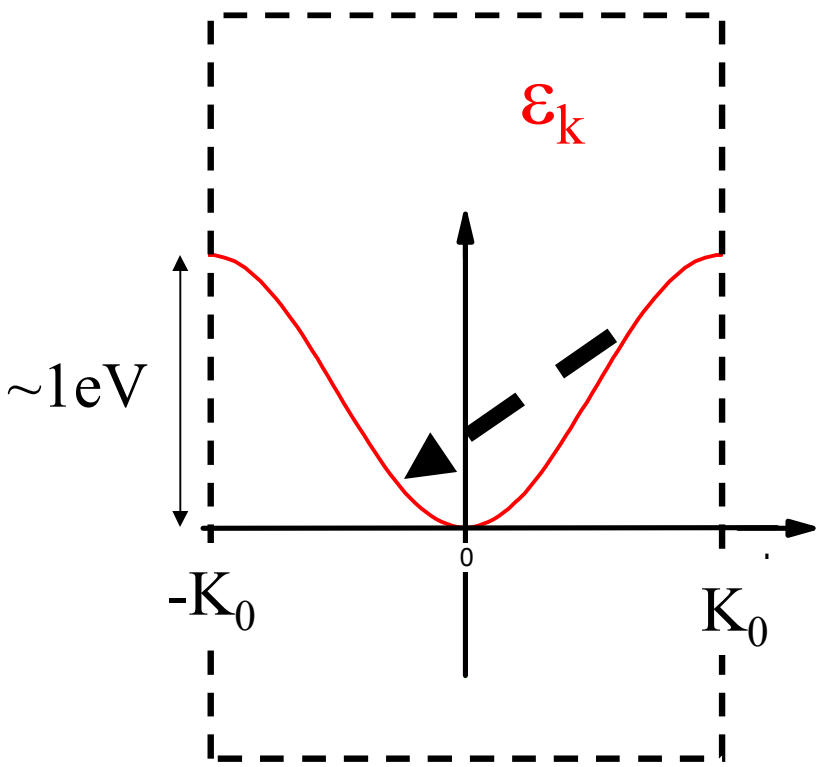
a: lattice constant

Why Bloch oscillation?

- THz application – frequency tunable



Problems in achieving Bloch oscillation



3D crystal

- Very high electric field

- Electron is scattered before it can complete a full oscillation

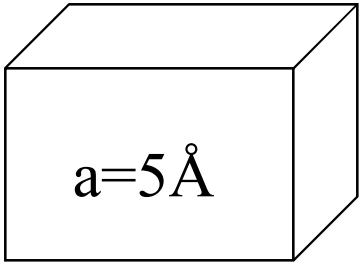
Scattering mechanisms:

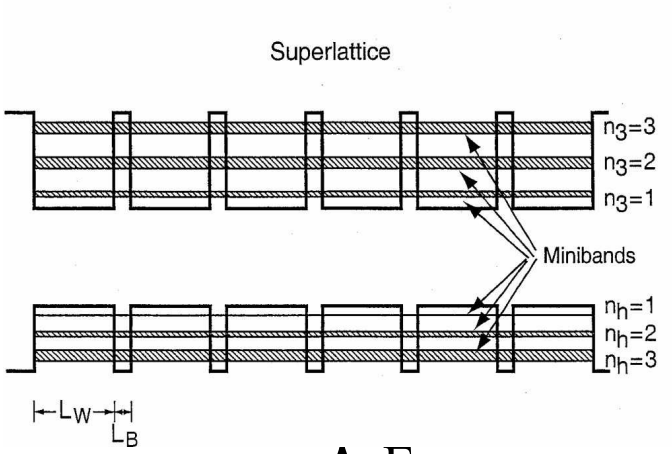
- Impurities
- Phonons

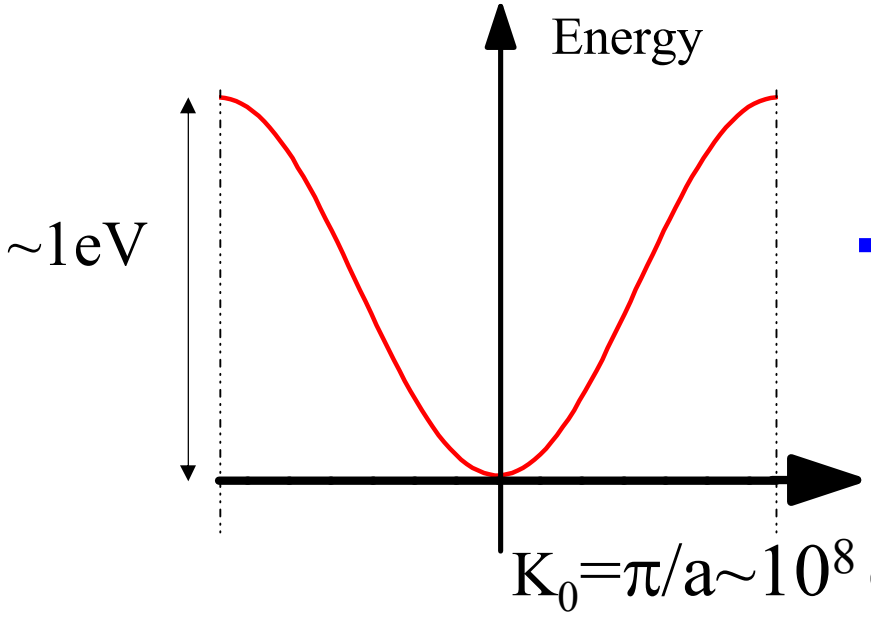
1D vertical superlattice

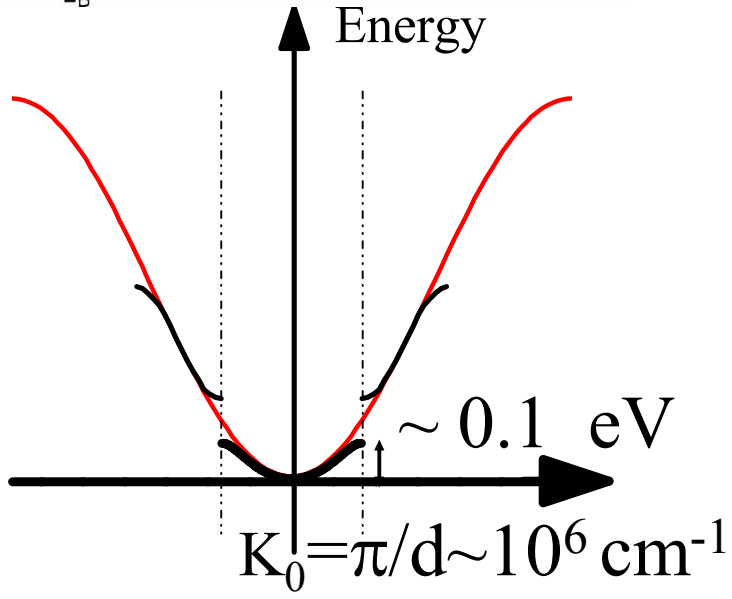
Esaki and Tsu, 1975

3D crystal









Issues in 1D superlattice

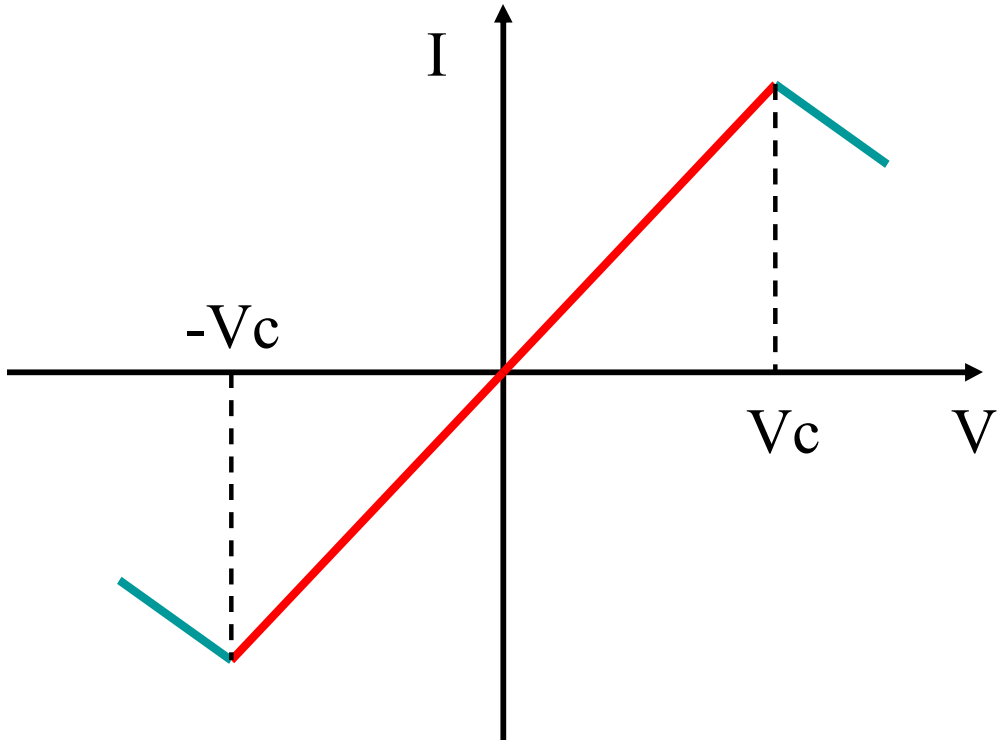
- formation of high electric field domains
- electron – phonon scattering
- impurity scattering
- ….

New approach – 2D quantum dot superlattice

Dmitriev and Suris, Semiconductors 35, 212 (2001)

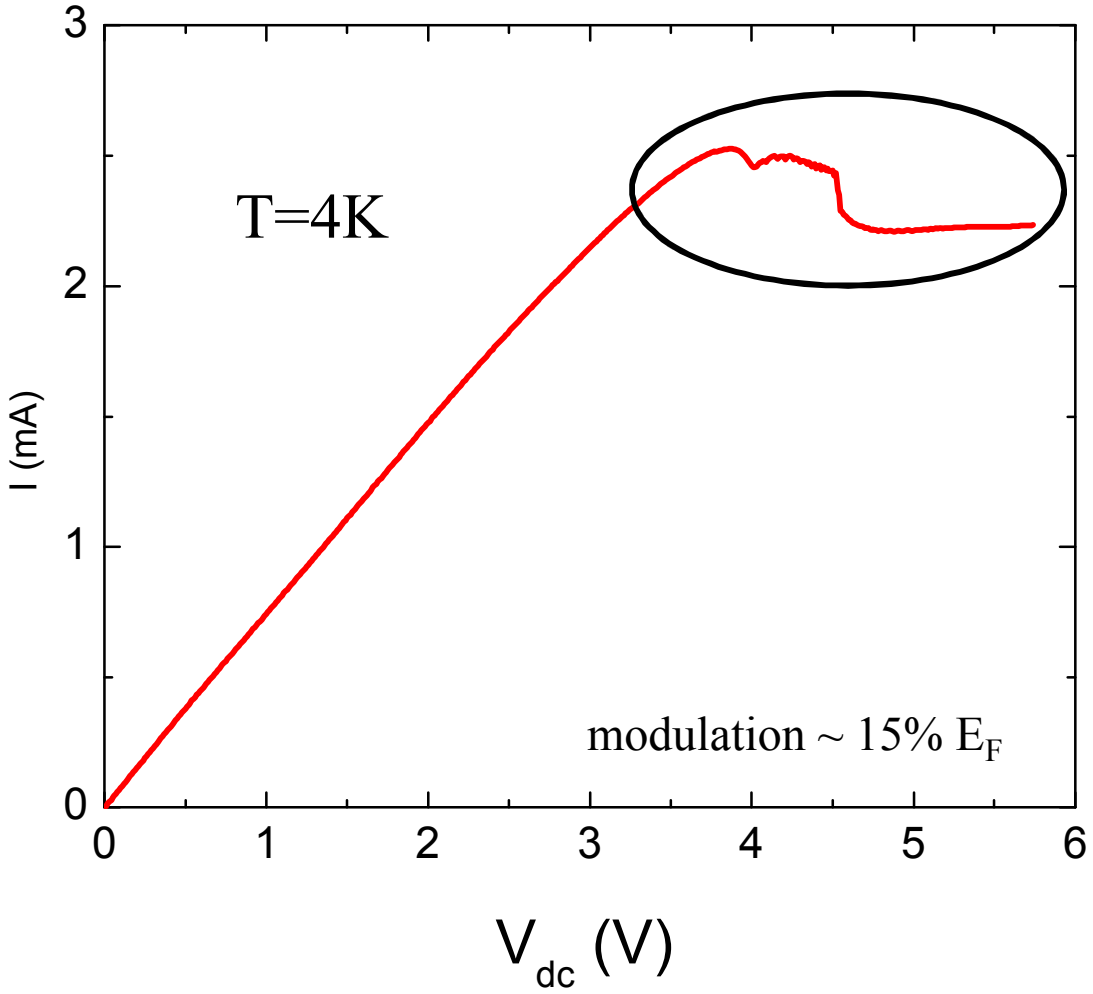
- 3D-quantum confinement, suppress electron-phonon scattering
- High sample quality, reduce disorder scattering
- 2D dimensionality, prevent formation of electric field domains
- Compatible with existing techniques, interferometric lithography

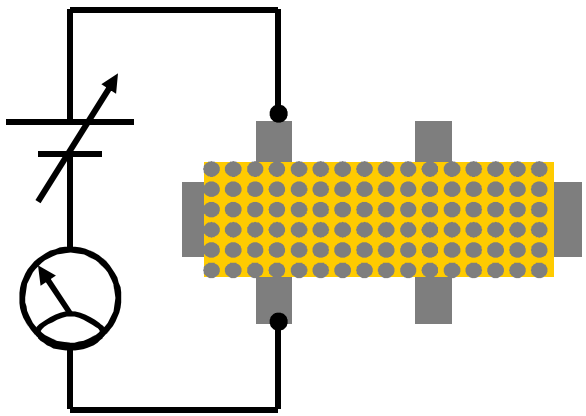
One of the signatures for Bloch oscillation is negative differential conductance (NDC)



I – V measurement in 2D QDSL

Negative Differential Conductance (NDC) !

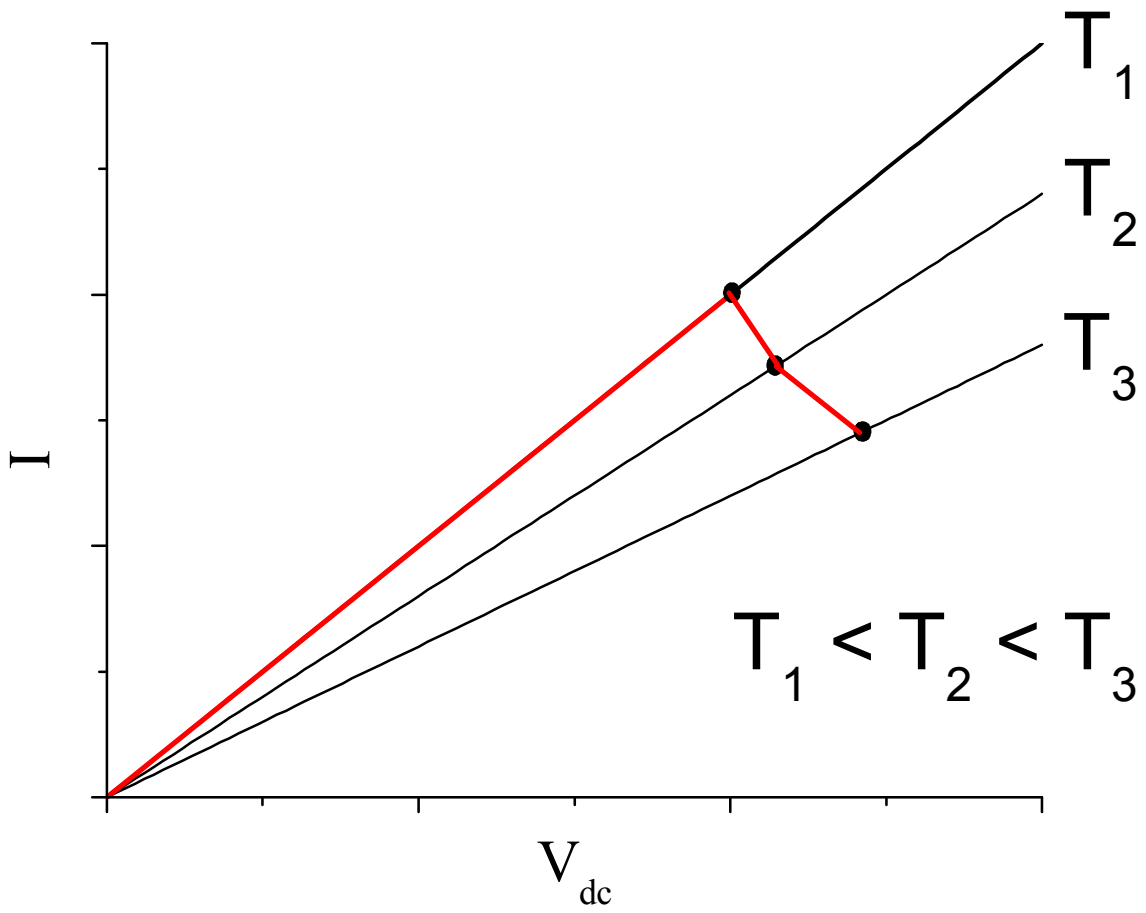




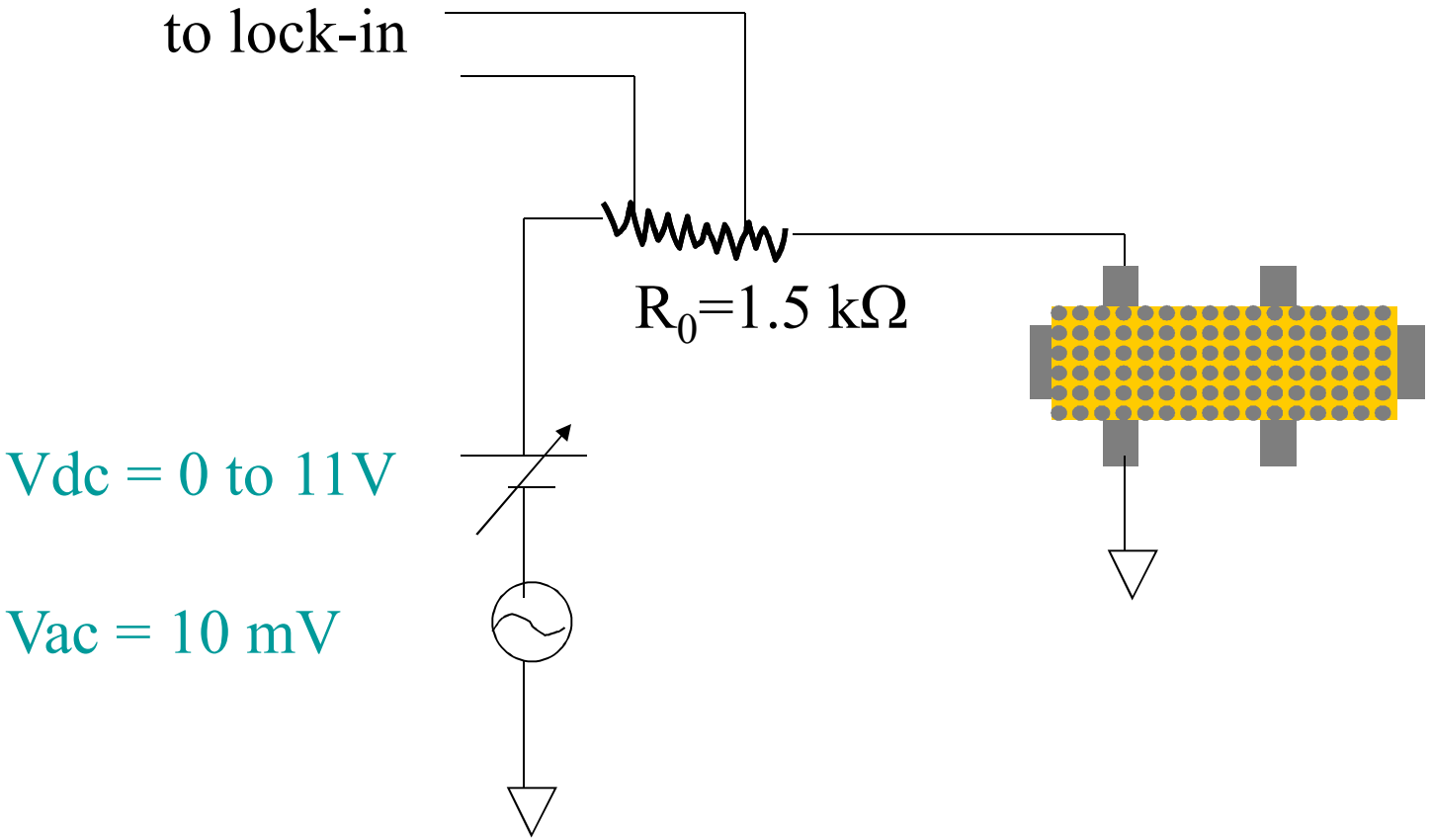
Physical origin of NDC ?

- Bloch oscillation?
- high field domains?
- thermal runaway?

Thermal runaway origin?



Temperature dependent conductance can give rise to an apparent NDC

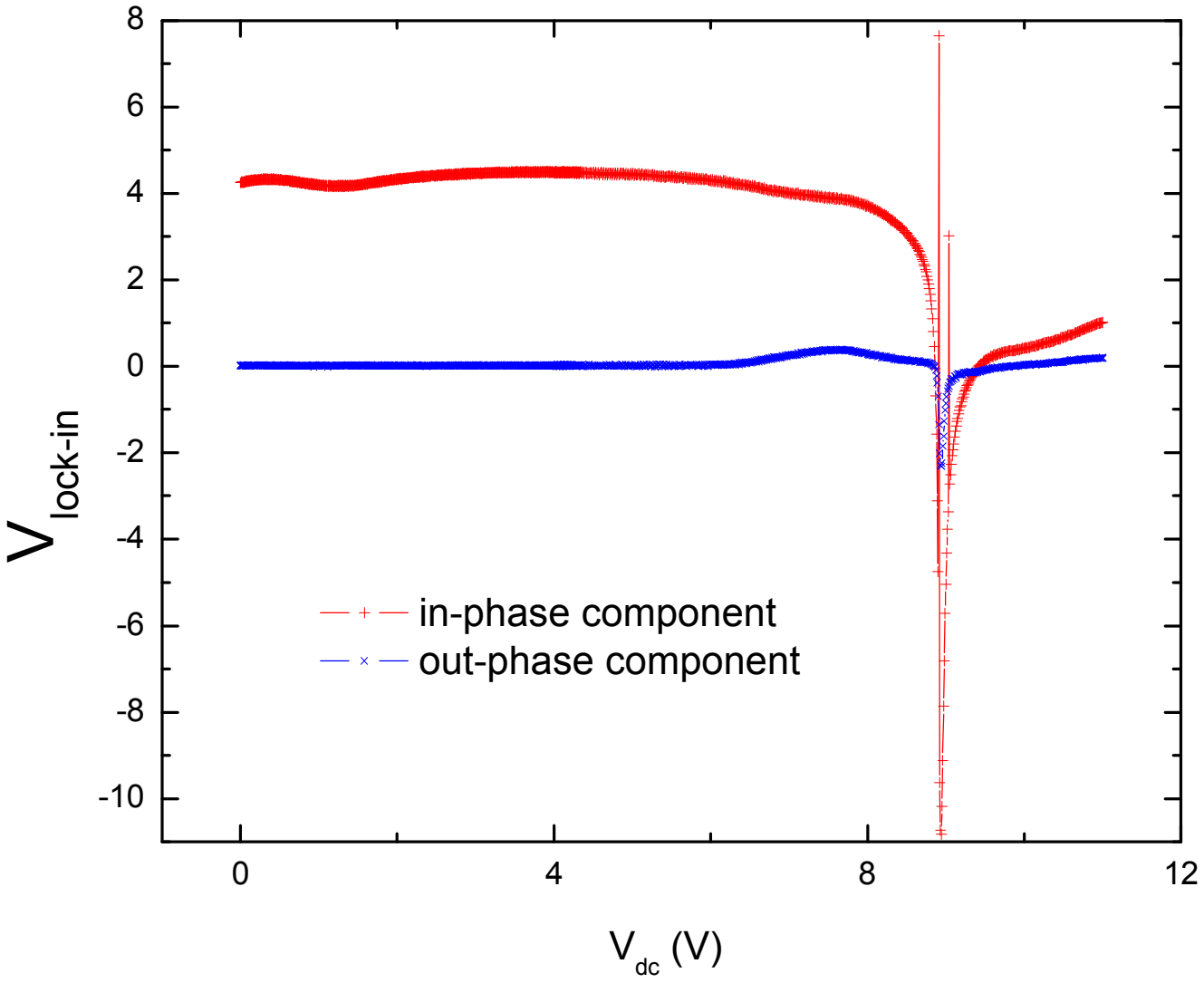


$V_{lock\text{-}in} = R_0/(R_0+r) \times Vac$

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

- **if due to temperature, r positive, $V_{lock\text{-}in} > 0$**
- **if r negative, and $|r| > R_0$, $V_{lock\text{-}in}$ is negative**

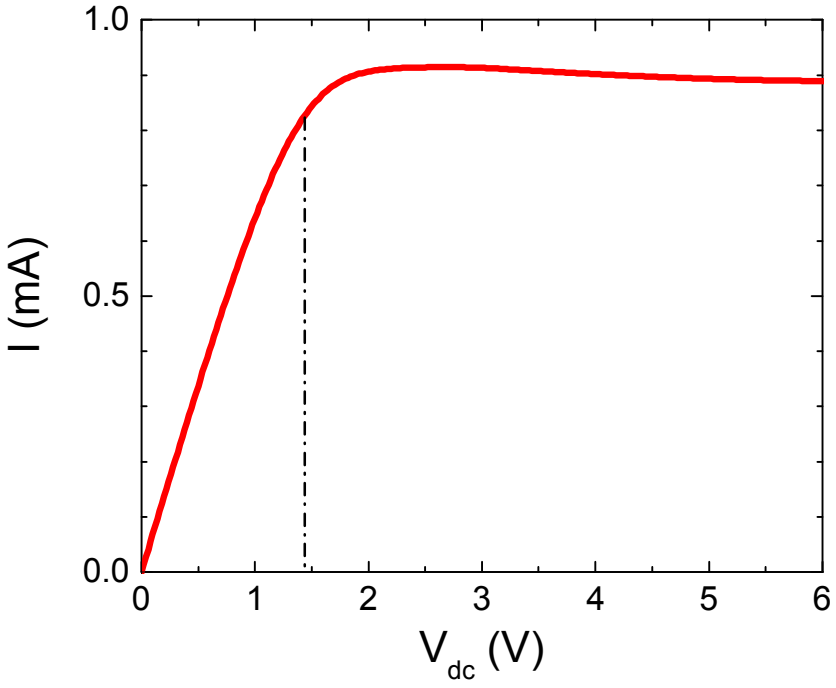
True negative differential conductance

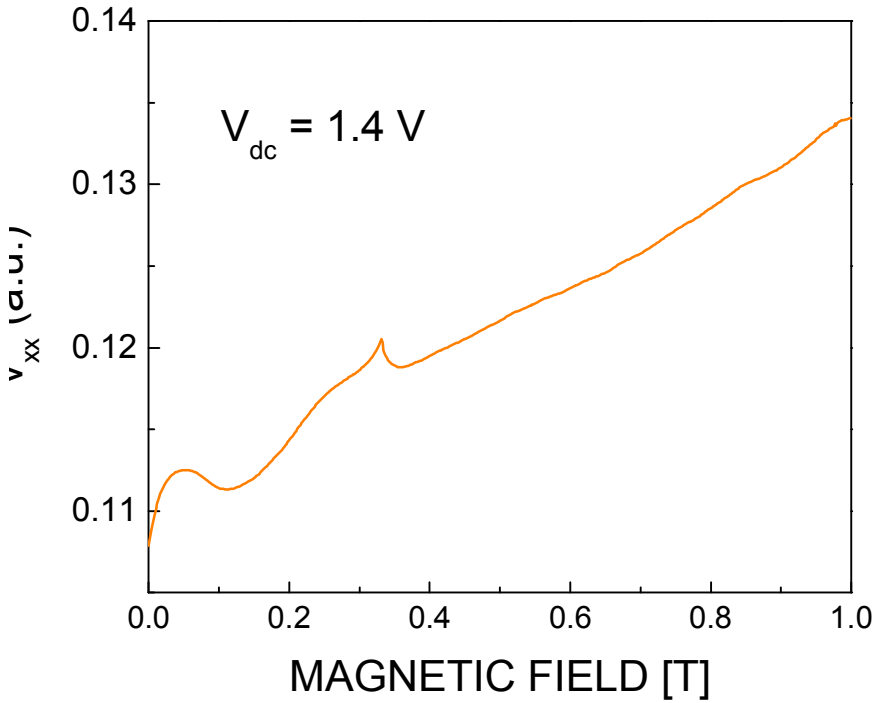


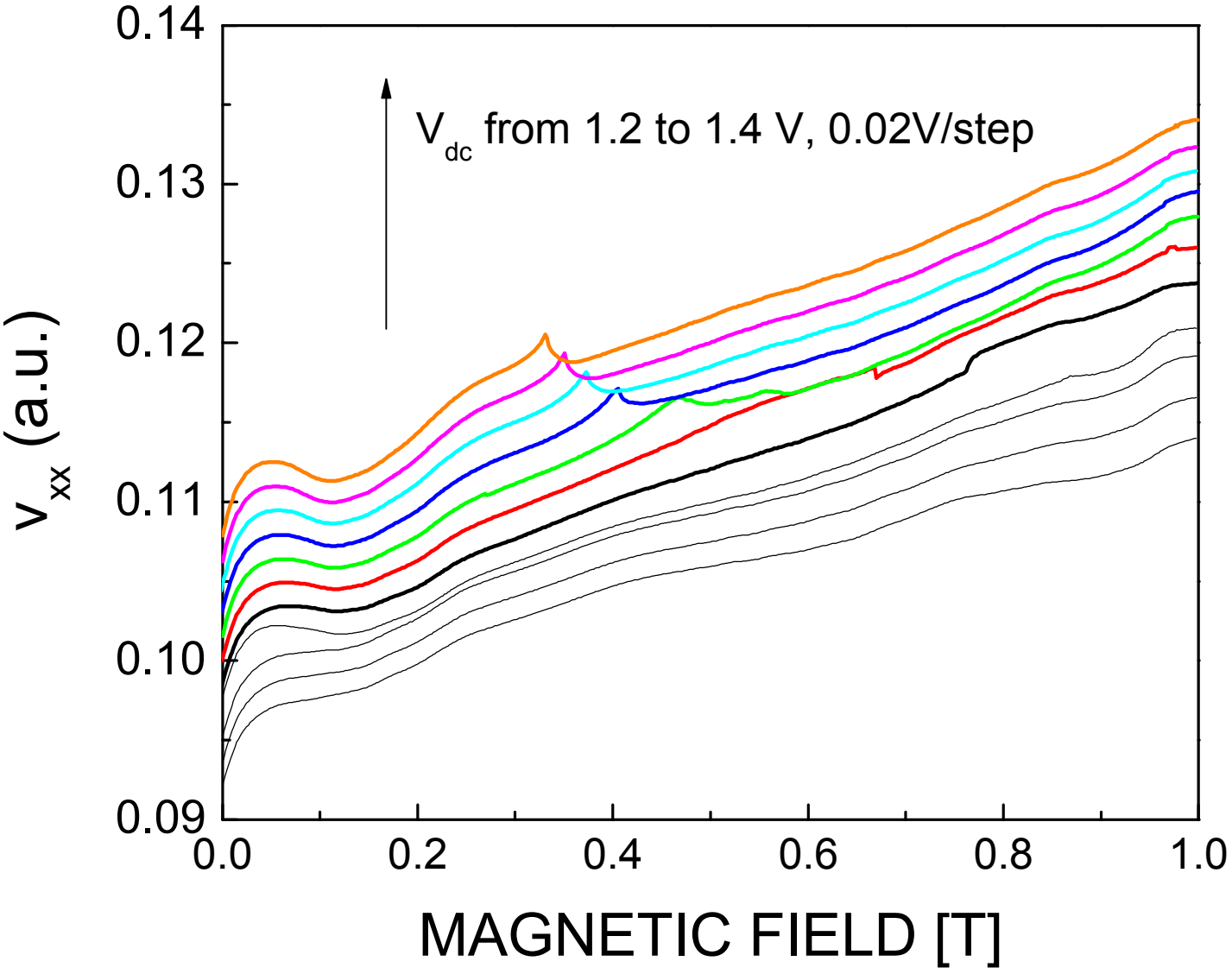
Physical origin of NDC ?

- Bloch oscillation?
- high field domains?
- ~~thermal runaway?~~

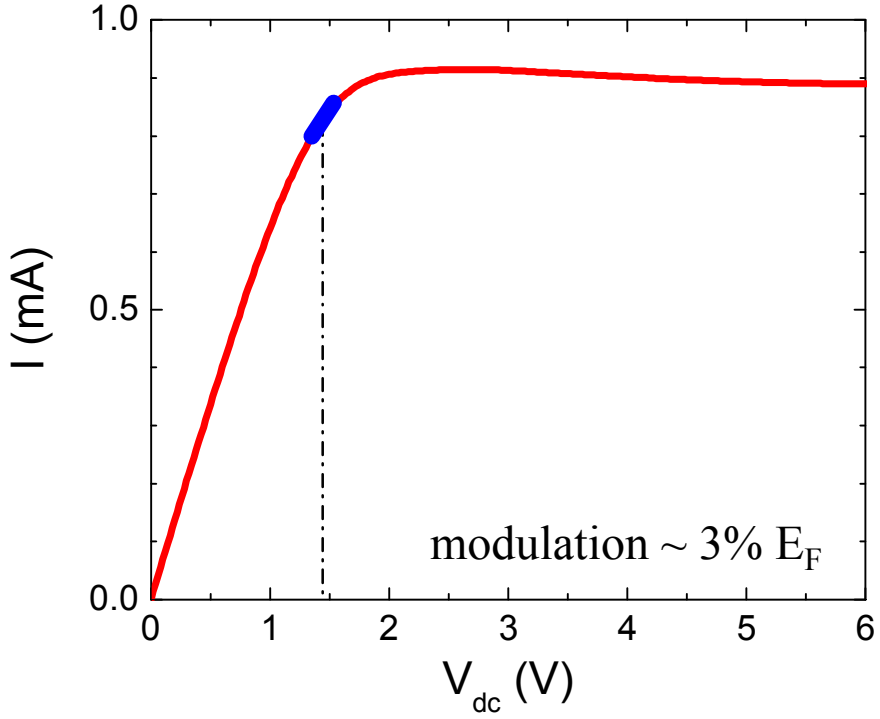
More evidence of Bloch oscillation

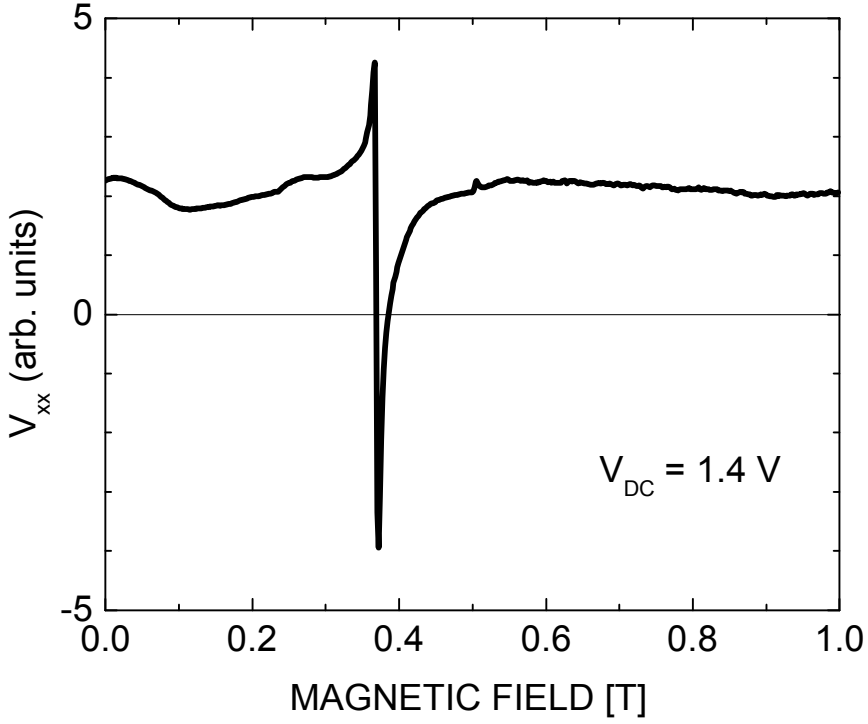


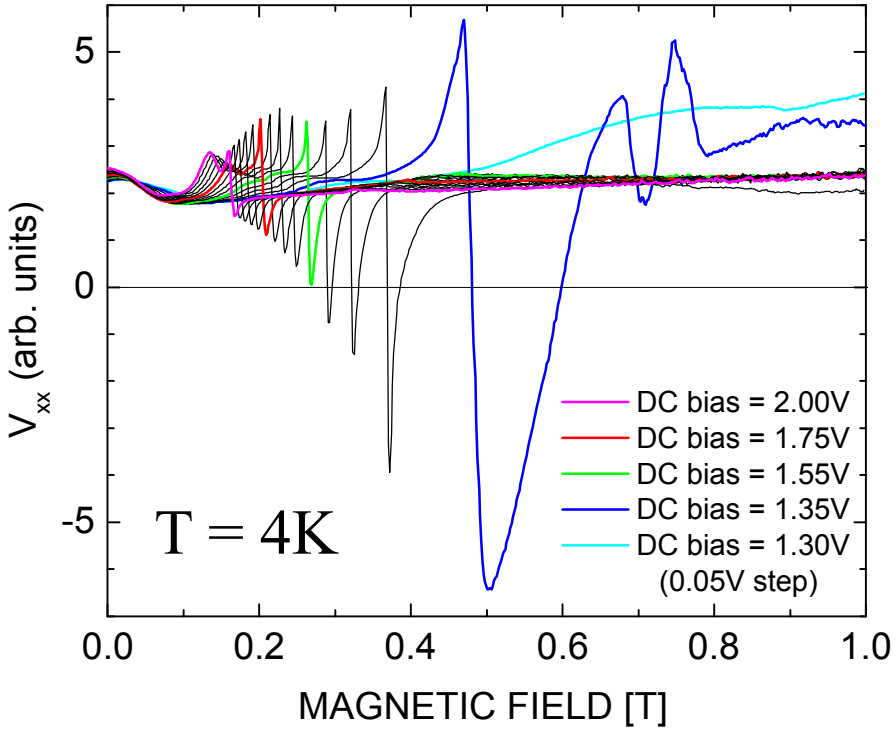


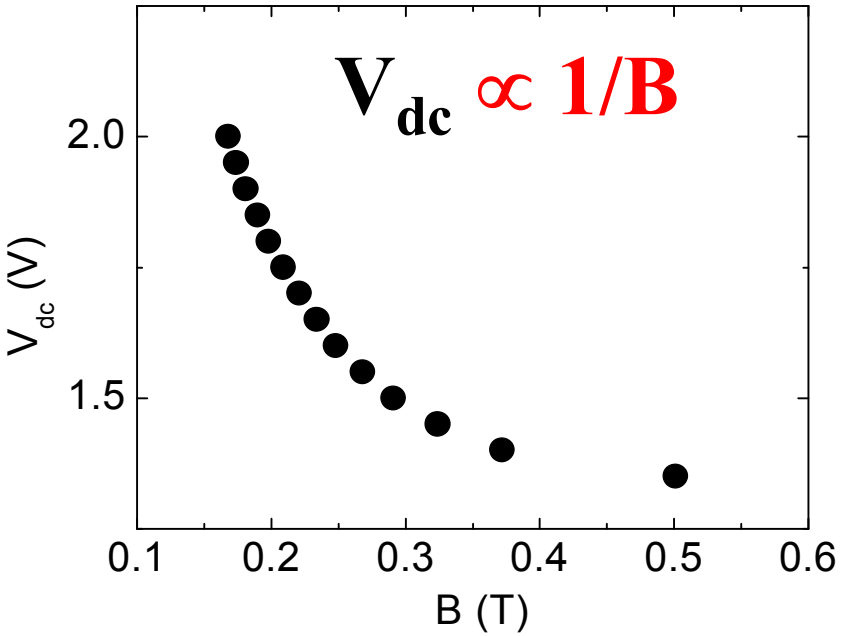

0.14
0.13
0.12
0.11
0.10
0.09
v_{xx} (a.u.)
V_{dc} from 1.2 to 1.4 V, 0.02V/step
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]

Derivative measurement

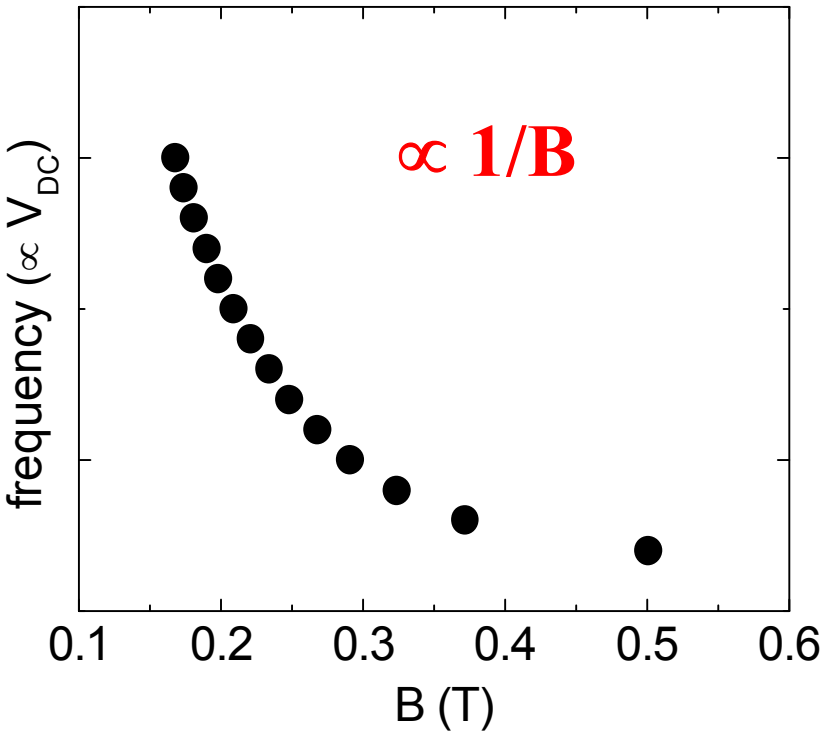


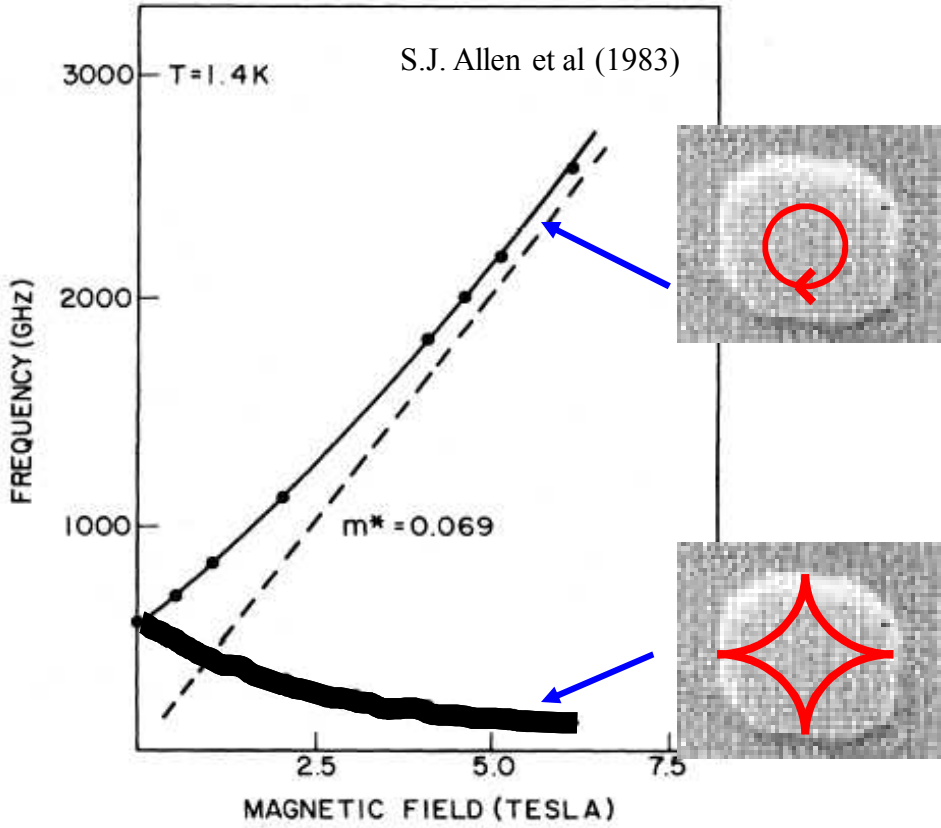



5
0
-5
V_{xx} (arb. units)
T = 4K
DC bias = 2.00V
DC bias = 1.75V
DC bias = 1.55V
DC bias = 1.35V
DC bias = 1.30V
(0.05V step)
0.0
0.2
0.4
0.6
0.8
1.0
MAGNETIC FIELD [T]


$V_{dc} \propto 1/B$
2.0
1.5
V_{dc} (V)
0.1
0.2
0.3
0.4
0.5
0.6
B (T)

Edge magnetoplasmon resonance in QDSL?





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

Summary:

❖ Weakened ν=1 quantum Hall state

- spin effect? Need tilting magnetic field measurements

❖ Evidence of Bloch oscillation in quantum dot array

- I-V measurement
- Edge magnetoplasmon resonance like behavior