QUANTUM EFFECTS IN THE CHARGE DENSITY WAWE COLLECTIVE MOTION

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LPS ORSAY

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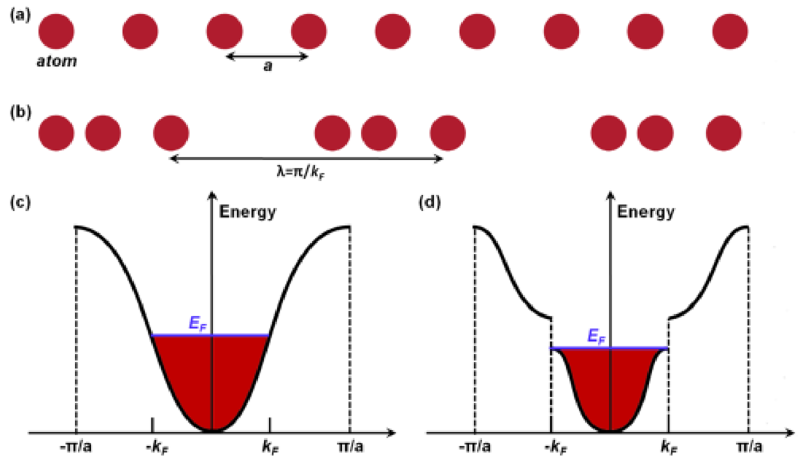
OUTLINE

1. Brief description of the CDW collective motion
2. Investigated compound $NbSe_3$:main properties
3. Contactless method for the CDW sliding
4. Experimental results
5. Conclusion

Charge density wave

$T > T_P$

$T < T_p$



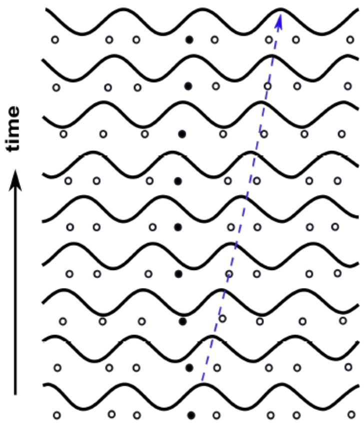
(Peierls, 1955)

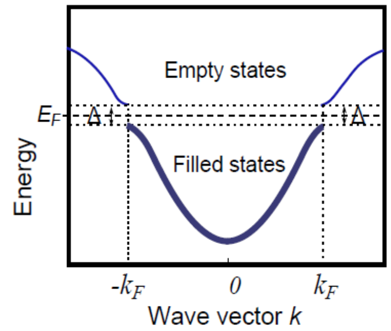
Peierls transition

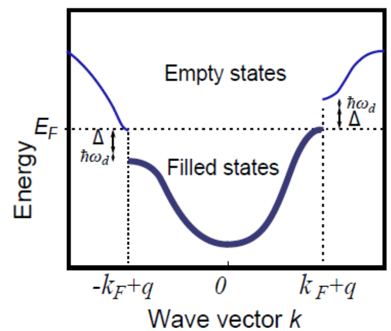
it is possible to lower the electronic energy of a 1D system by opening a gap at the Fermi level from the coupling of a $2k_F$ wave vector with the underlying lattice. The introduction of a periodic potential due to atomic displacement having the periodicity of $2\pi/2k_F$ introduces a new Brillouin zone at $\pm k$F; that consequently opens a band gap at ε_F. For 1D systems the energy cost in distortion is always lower than the gain in electronic energy, making the transition favourable.

COLLECTIVE ELECTRON TRANSPORT OF THE CDW

Under external electric field







$$u(t) = u_0 \cos\left[Qna - \omega_d t\right]$$

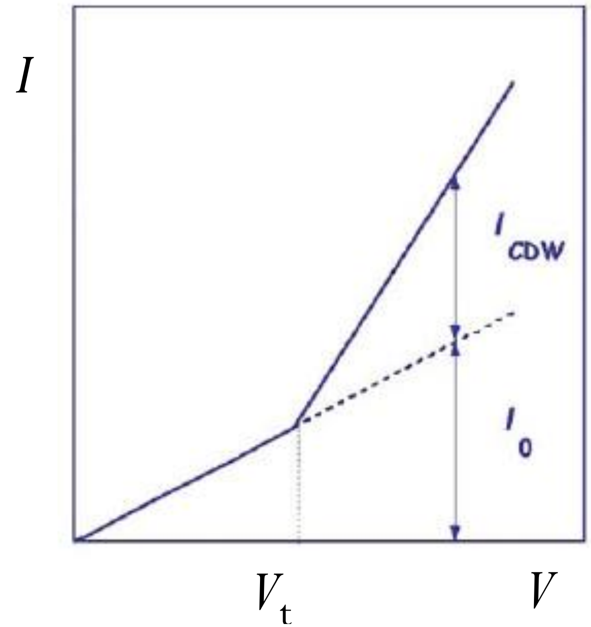
$$\rho(x,t) = \rho_0 \cos\left[Qx - \omega_d t\right]$$

$$v_d = \omega_d / Q$$

$$Q = 2k_F$$

$$J = nev_d$$

IV curve



$$I = I_n + I_{\mathrm{C/S\,DW}}$$

Fröhlich superconductivity (1957)

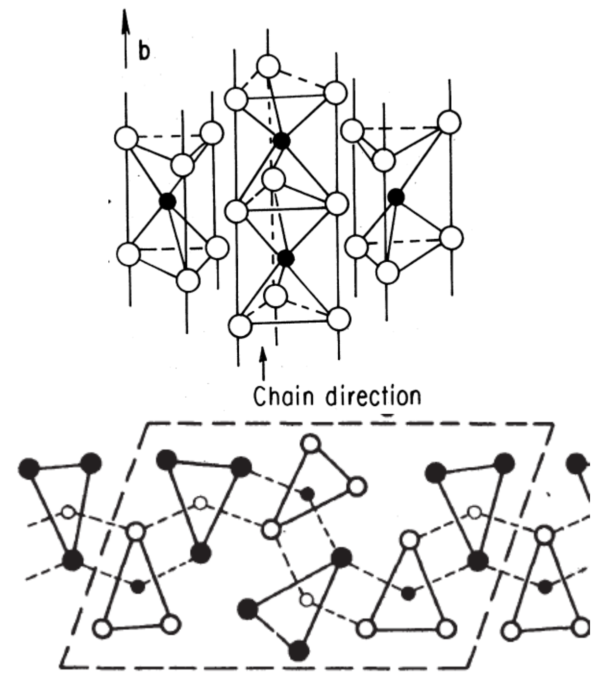
The states with current flow if the energy gap is displaced with the electrons and remains attached to the Femi surface. There is no state available for relaxing energy. Such motion is without dissipation and the compound in principle may become superconducting.

Two Peierls transitions:

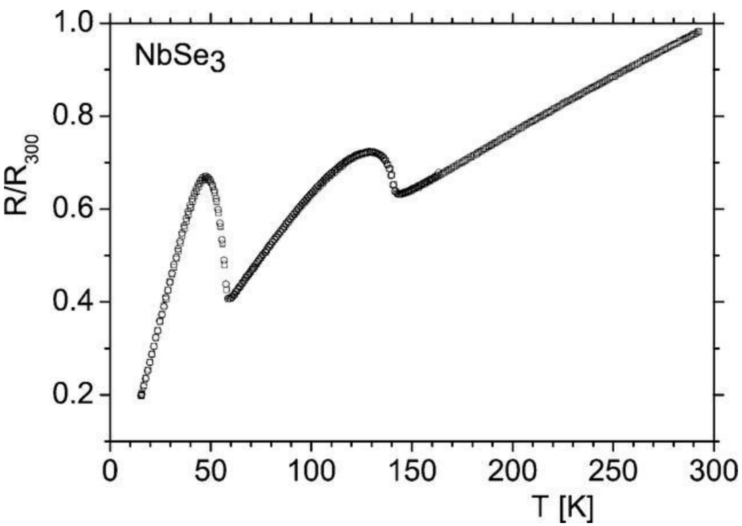
T_{P1} = 144K and T_{P2} = 59K

$Q_1 = (0, 0.241b*, 0)$ – chain of III type

$Q_2 = (0.5, 0.260b*, 0.5)$ – chain of I type



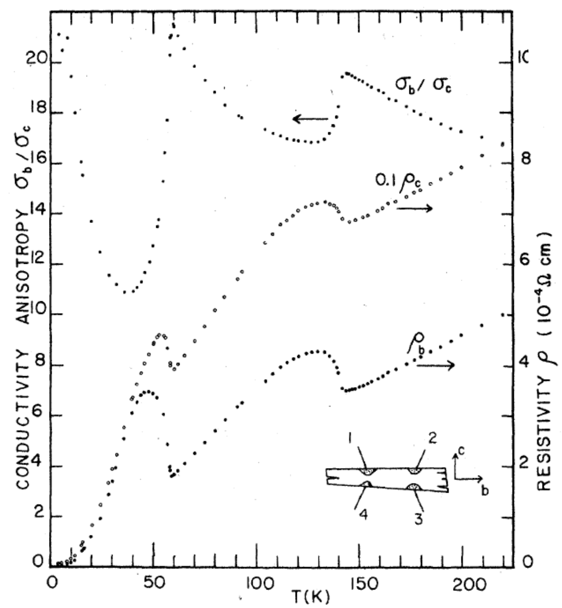
$NbSe_3$



Semimetal groung state

300 K n ~10^{21} cm^{-3}

4 K n ~10^{18} cm^{-3}



anisotropy

$\sigma_b/\sigma_c \approx 20$

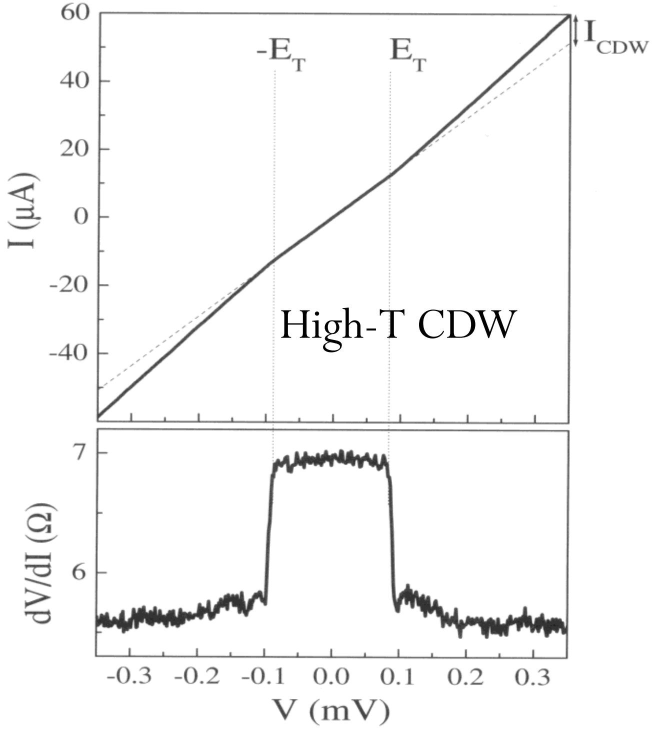
$\sigma_b/\sigma_a \approx 10^3$ (300K)

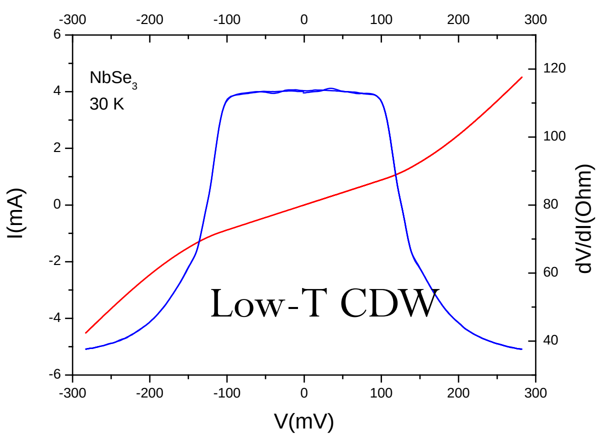
10^5 (4 K)

N.P. Ong and J.W. Brill, PRB, 18, 5265 (1978)

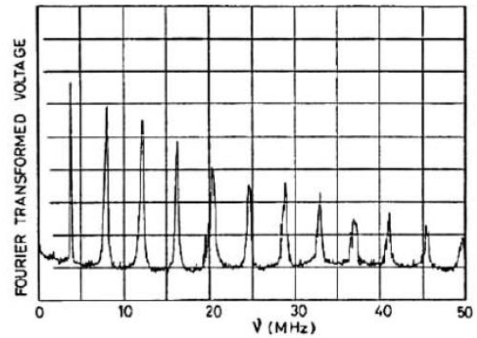
COLLECTIVE ELECTRON TRANSPORT in $NbSe_3$

IVs



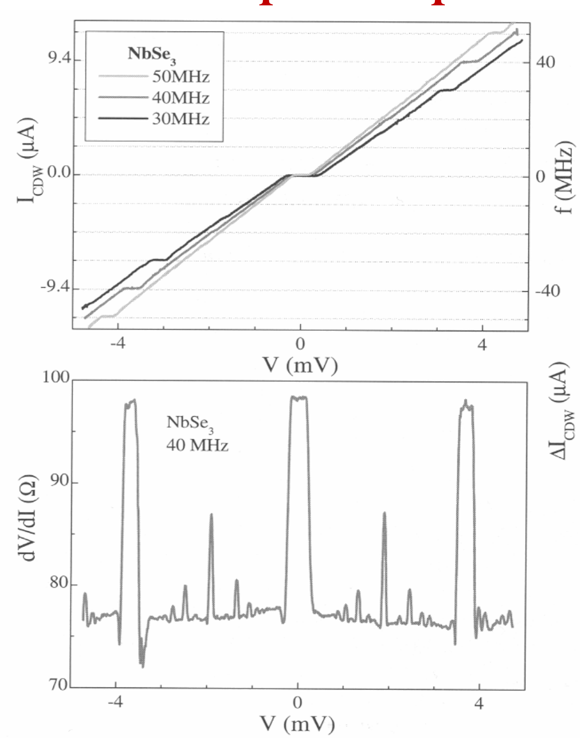


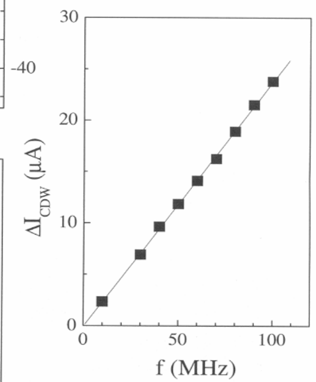
Narrow band nois



$I_{CDW}^{(ch)} / F = 2e$

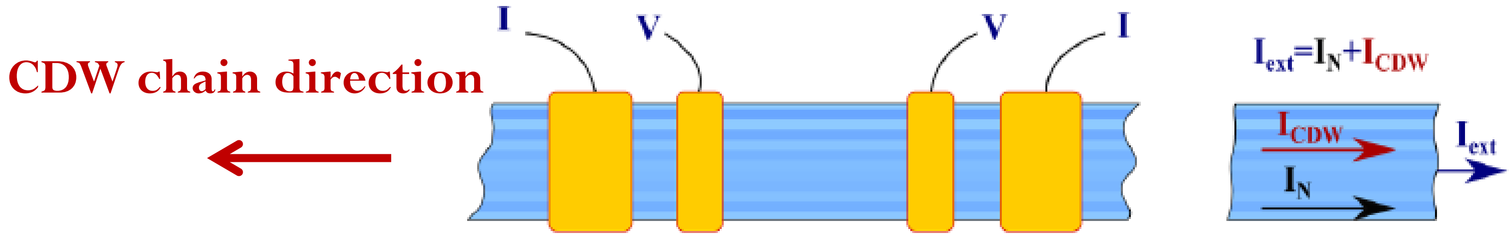
Shapiro steps

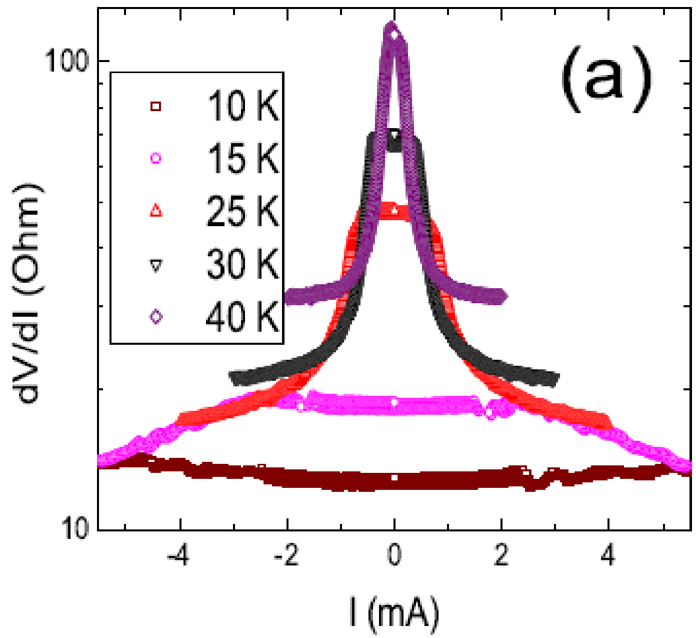


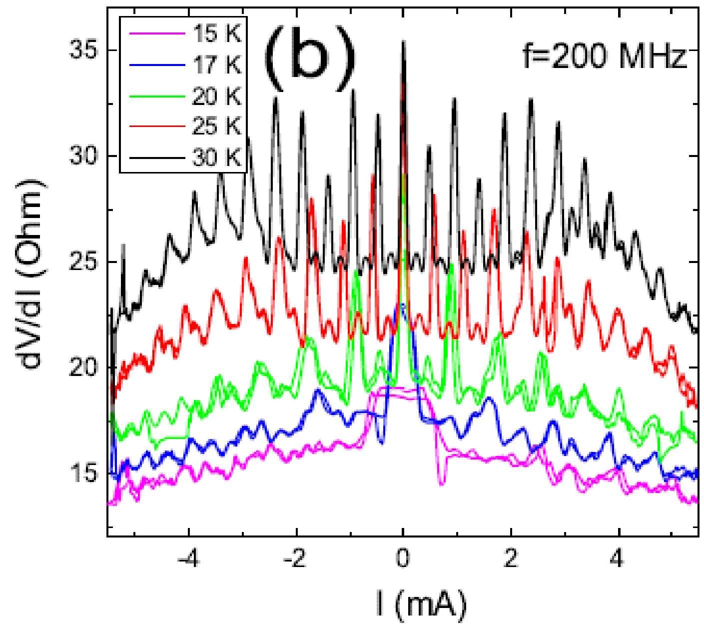


Problems in sliding of low-T CDW in $NbSe_3$

in convention measurement configuration







Low temperature problems:

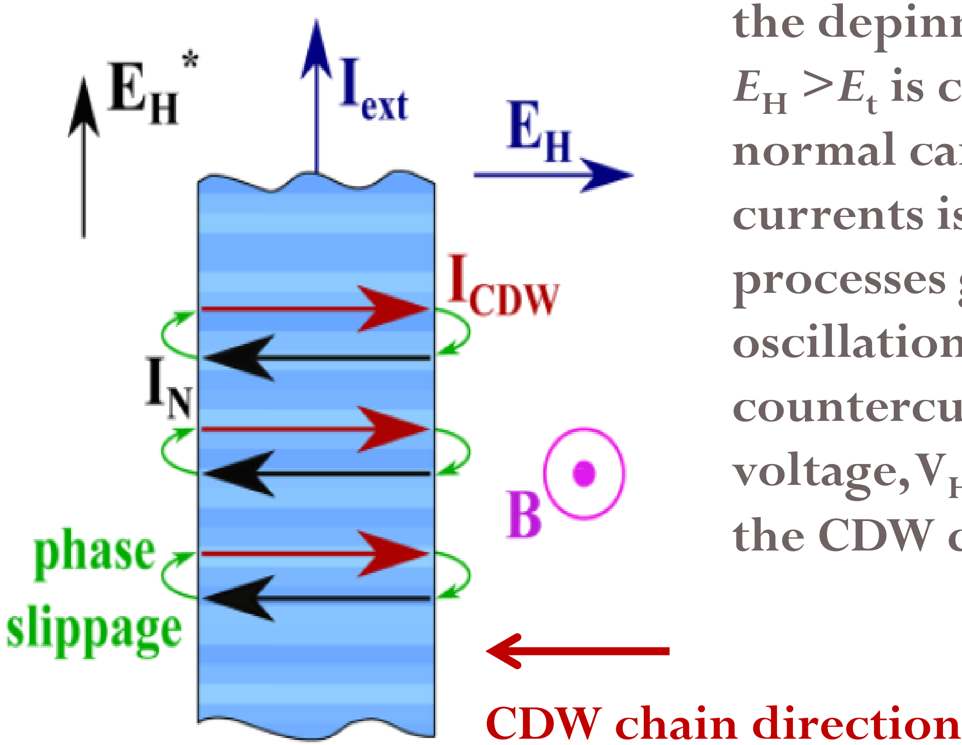
1. CDW can not slide at low T?
2. Joule heating?
3. Influence of co-directional normal carriers current?

QUESTION: **Is it possible another way to produce electric field?**

ANSWER: **YES**

***HALL ELECTRIC FIELD*:**

current directed transverse the chain + perpendicular magnetic field

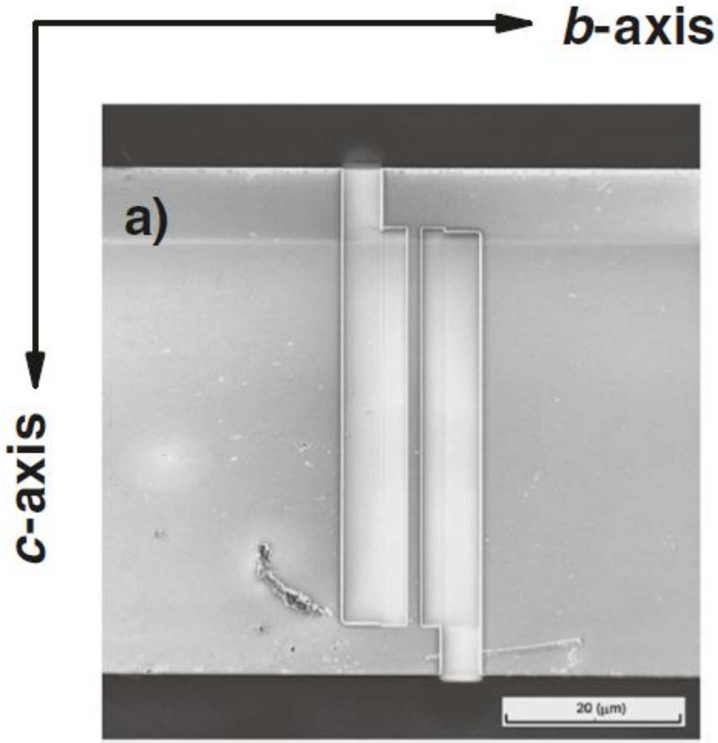


Hall electric field is oriented along the chains b-axis. Since the circuit is open along the b-axis, the depinning of the collective CDW current at $E_H > E_t$ is compensated by a counter-current of normal carriers. The zero-sum loop of these two currents is closed by periodic phase slip processes giving rise to spontaneous coherent oscillations. The appearance of the normal countercurrent gives rise to a secondary Hall voltage, V_H*, which is directly proportional to the CDW current.

No direct impact of magnetic field on the CDW

Structures

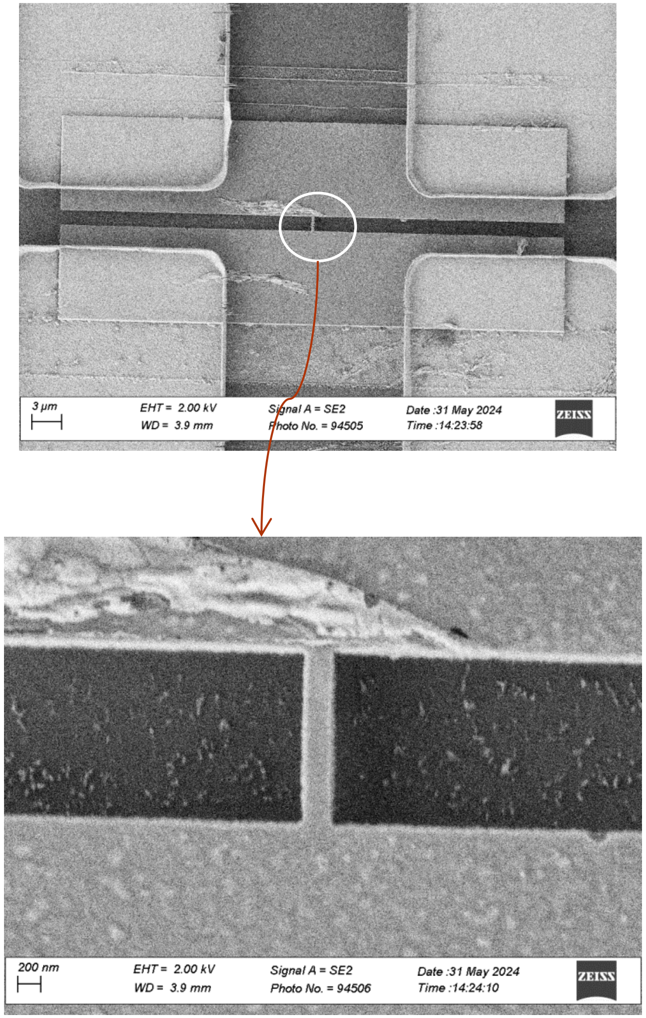
FIB



$W: \quad 0.6 - 6\ \mu m$

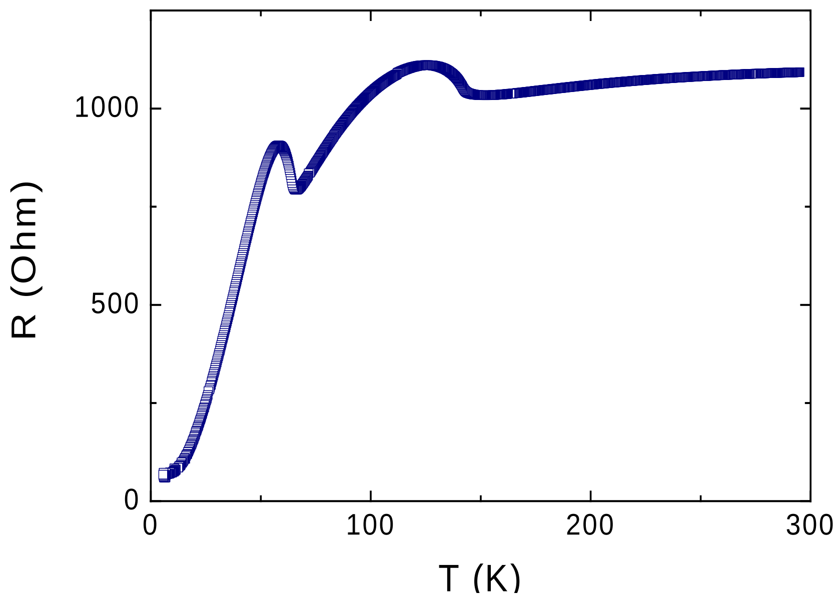
$L / W > 10$

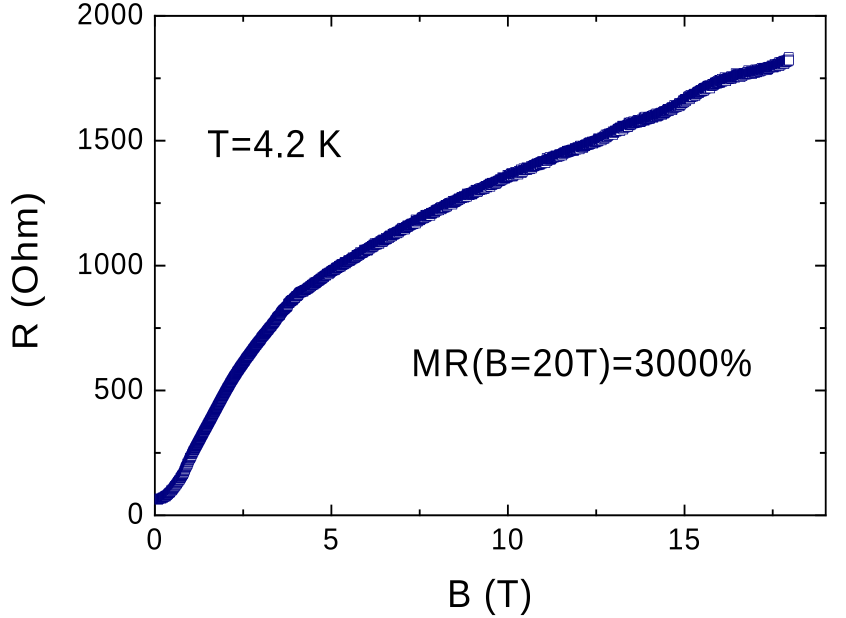
Electron lithography



$W: \quad 0.1 - 0.3\ \mu m$

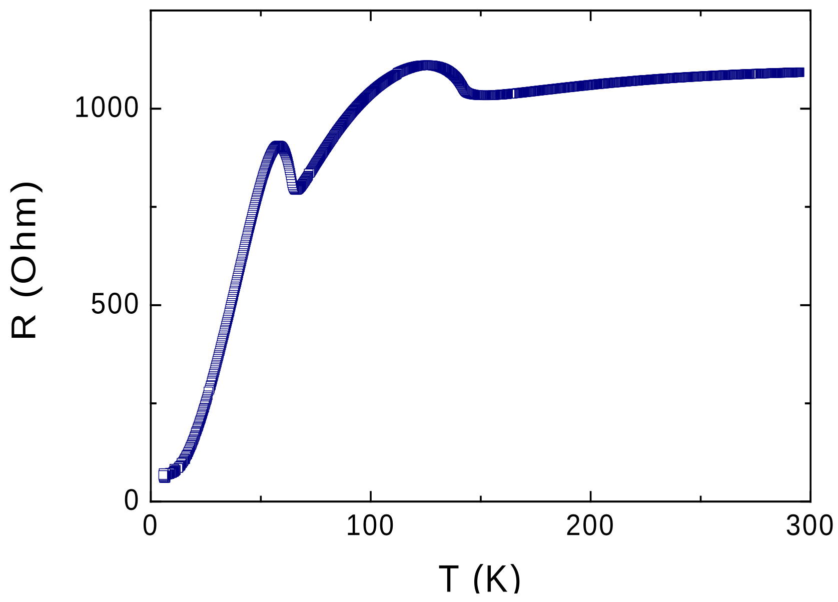
How it looks in experiment?

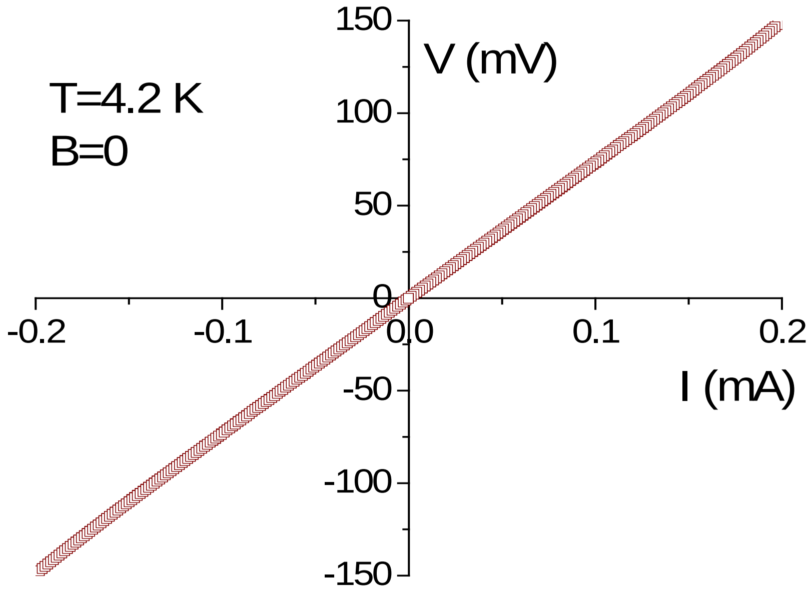


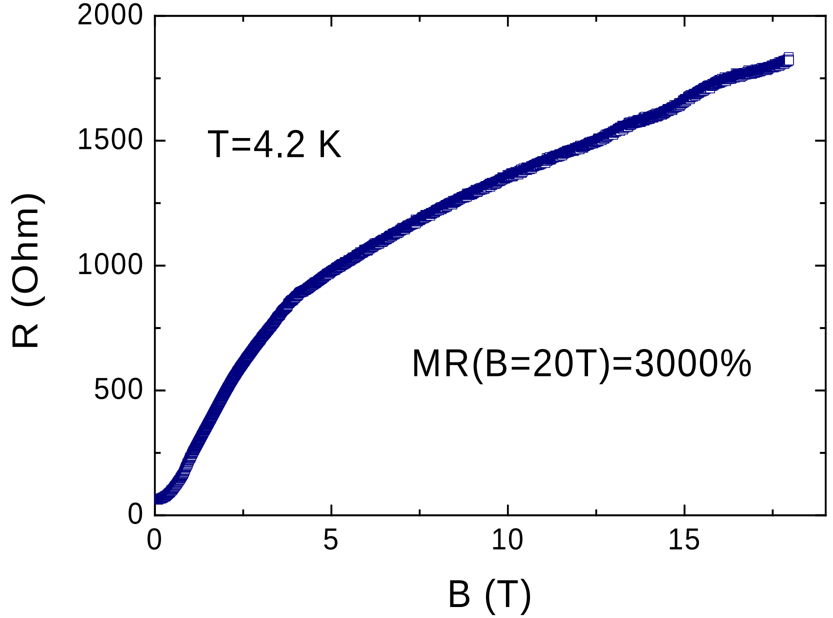


How it looks in experiment?

structure with w=3 μm







How it looks in experiment?

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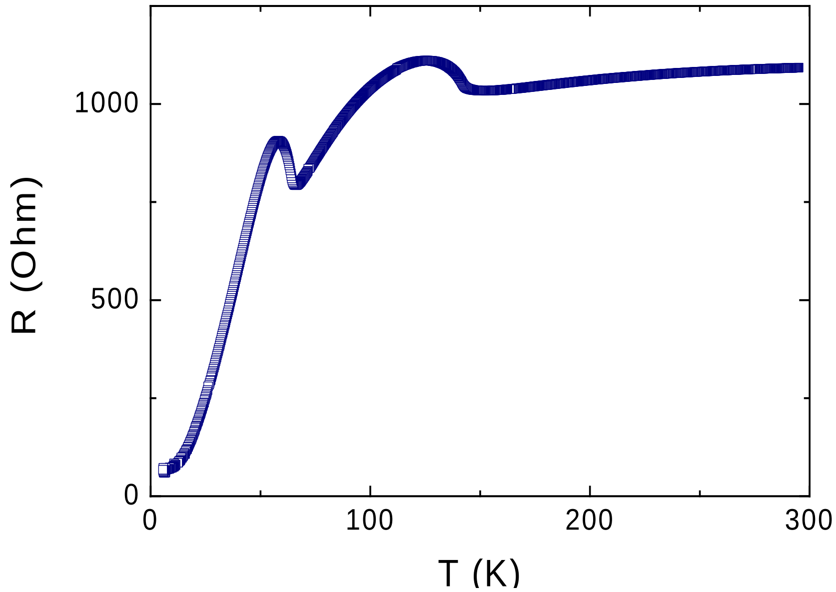
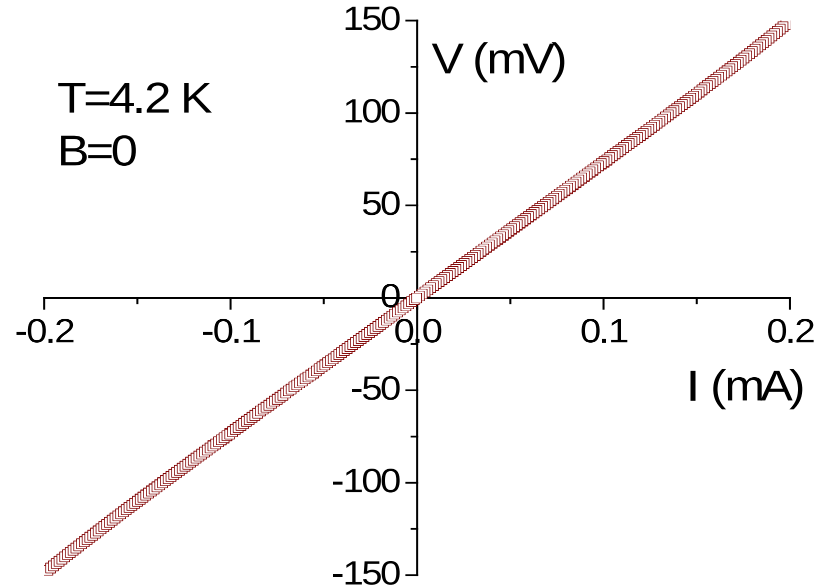
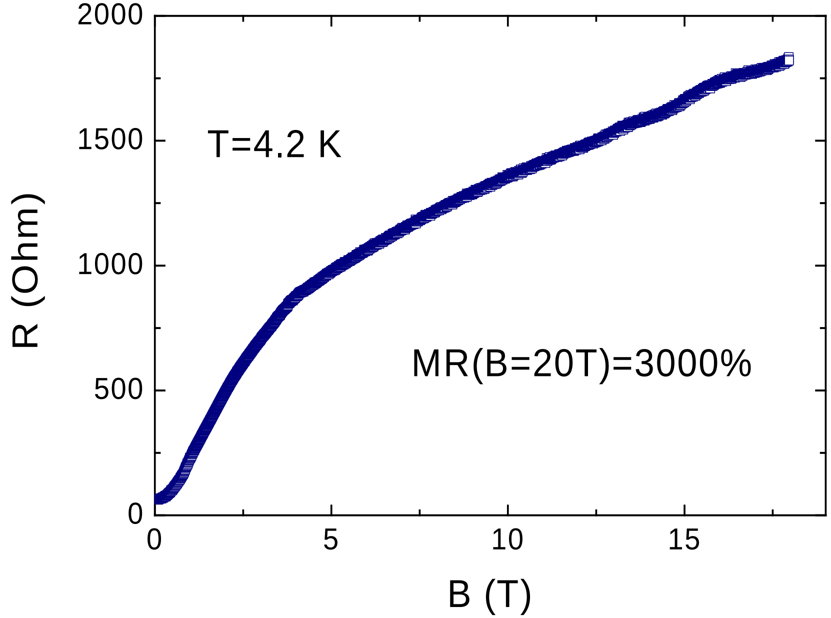
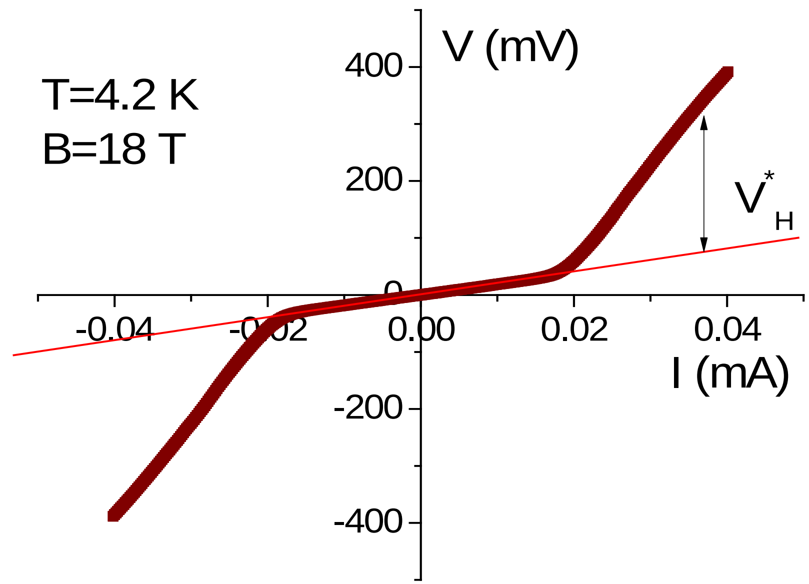


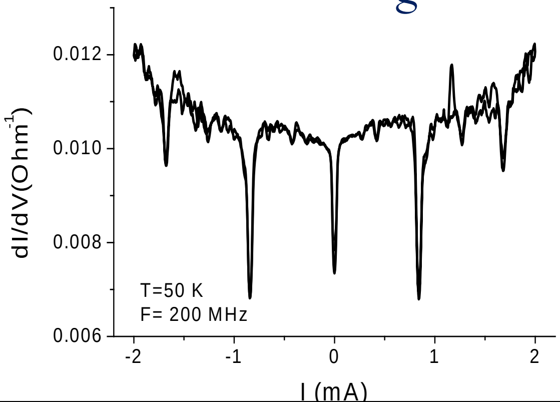


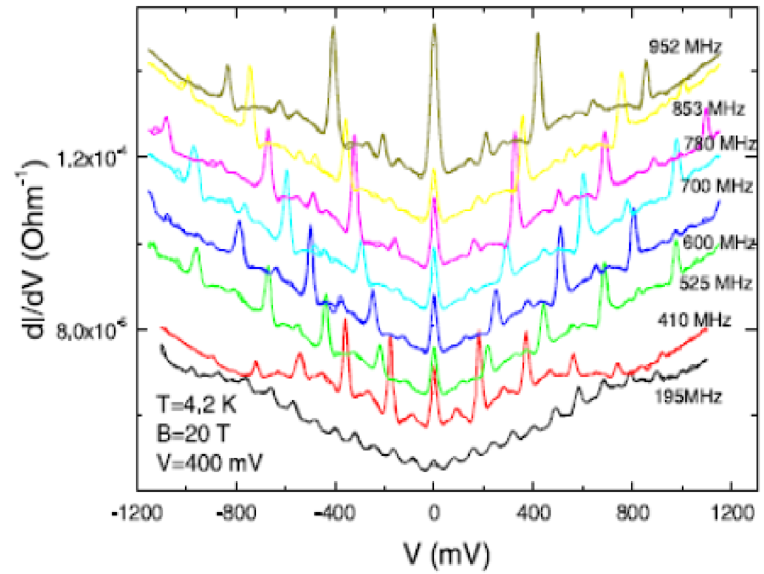




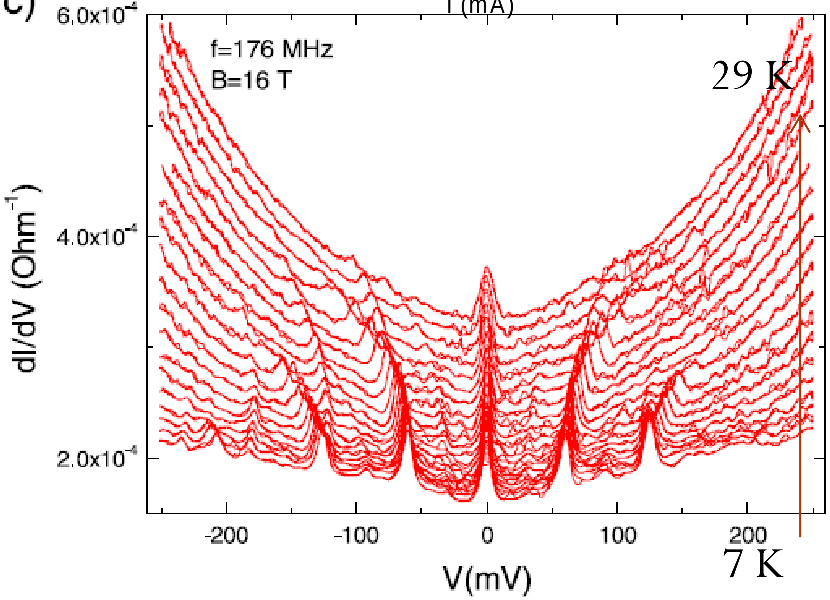
dc + ac electric fields
Shapiro steps

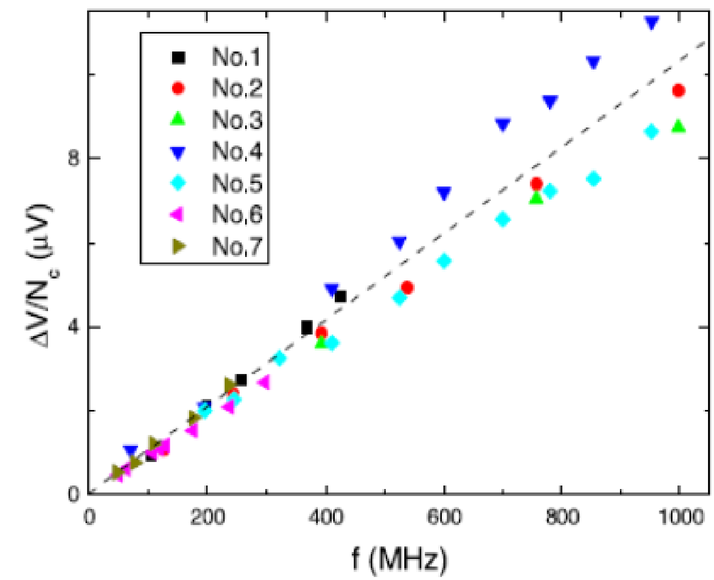
Convention configuration





c)

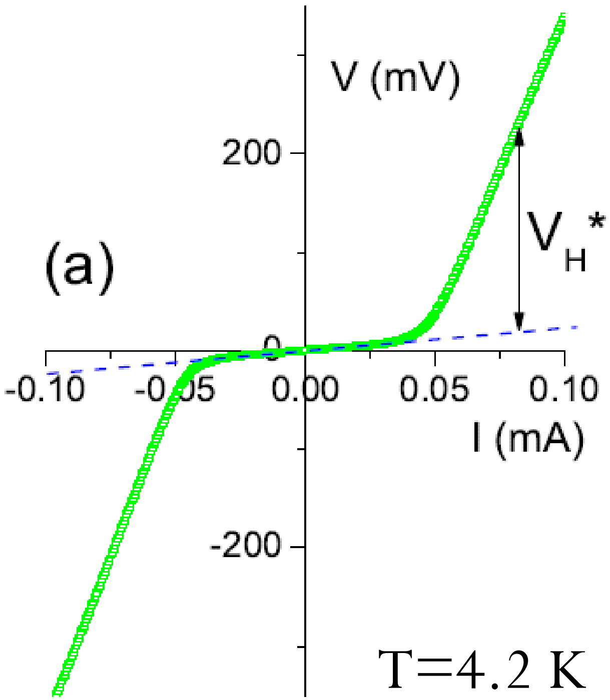




npj Quantum Materials, 61 (2017)

MEASURED IV

RECALCULATED IV



T=4.2 K

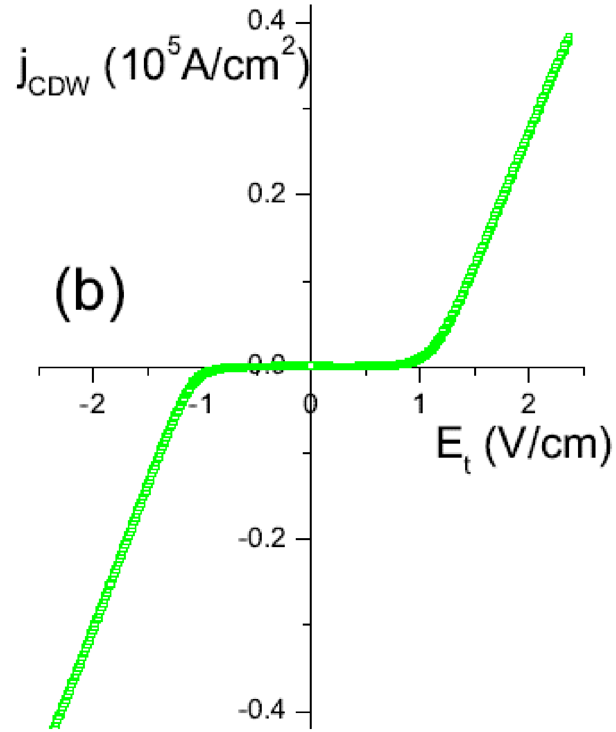
$$I_{CDW} = \frac{V_H^* d}{R_H B},$$

$$E = \frac{R_H I B}{d w}$$

l = 50 μm

w = 5 μm

d = 0.8 μm



at the current through structure I_0=100 μA

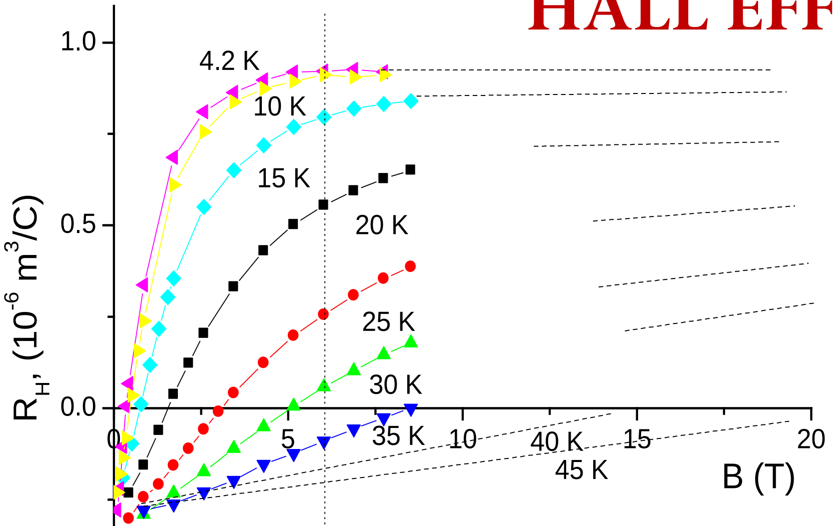
<u>I_{CDW}= 28 mA</u> at T=4.2 K and B=18 T

!!!

R_H - ?

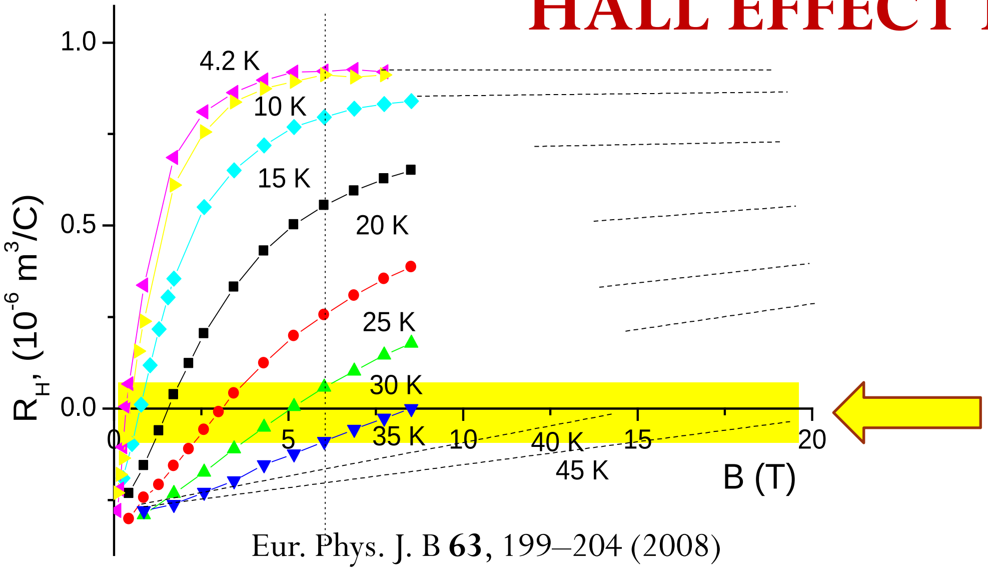
Separate experiments

HALL EFFECT IN $NbSe_3$



Eur. Phys. J. B **63**, 199–204 (2008)

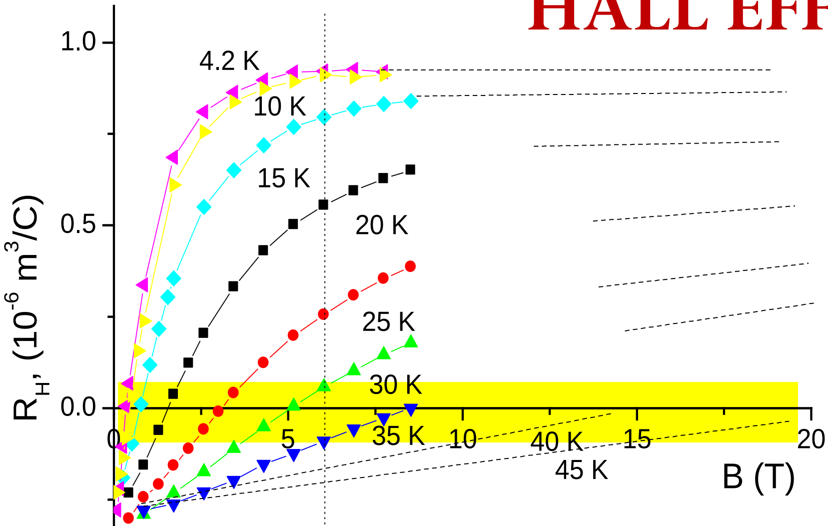
HALL EFFECT IN $NbSe_3$



Eur. Phys. J. B **63**, 199–204 (2008)

Region where the Hall electric field is not enough to reach the threshold electric field for the CDW sliding.

HALL EFFECT IN $NbSe_3$



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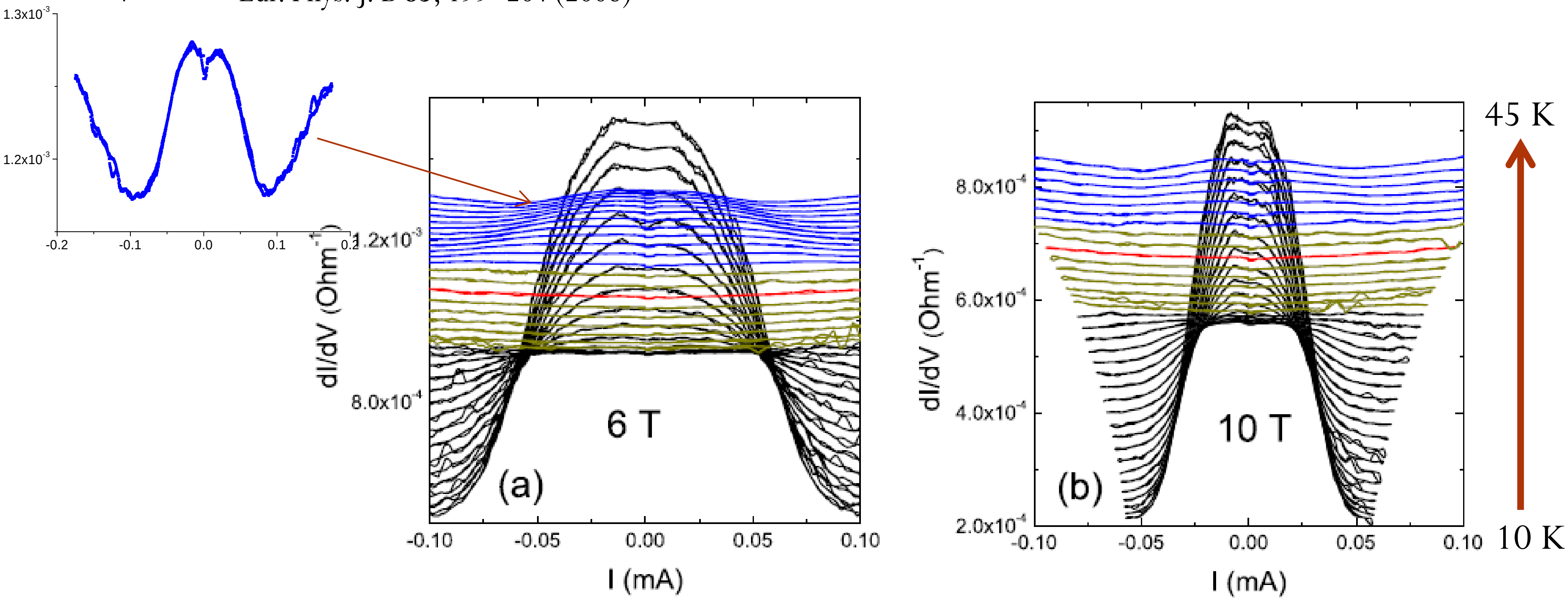


PRB, 100, 245126 (2019)

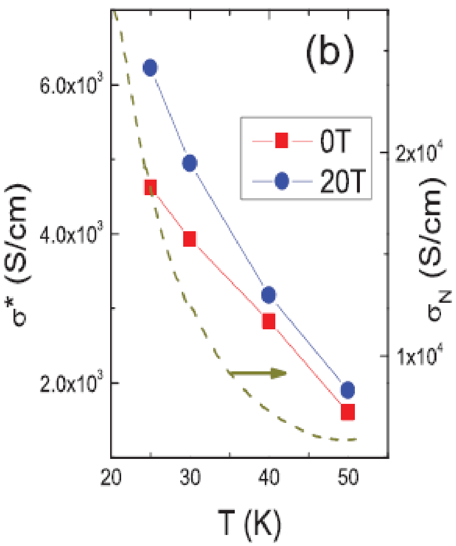
CONCLUSION 1:

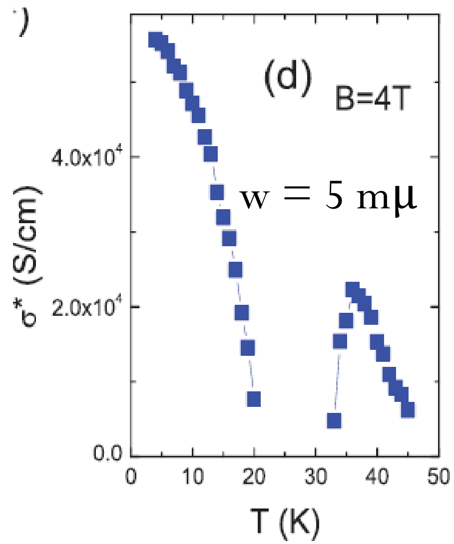
We have a new method for measuring IV curves in samples with ultra-short length.

What does it give us?

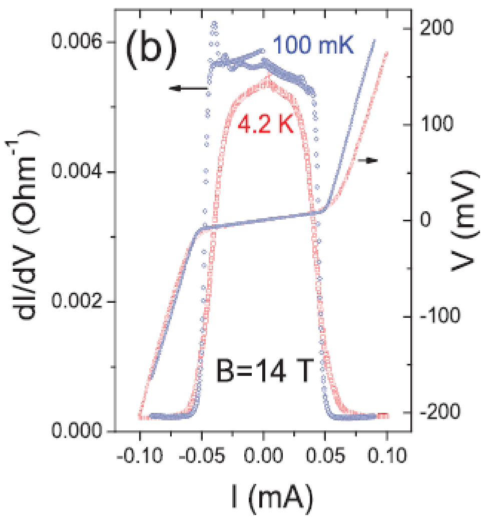
Conductivity of the CDW

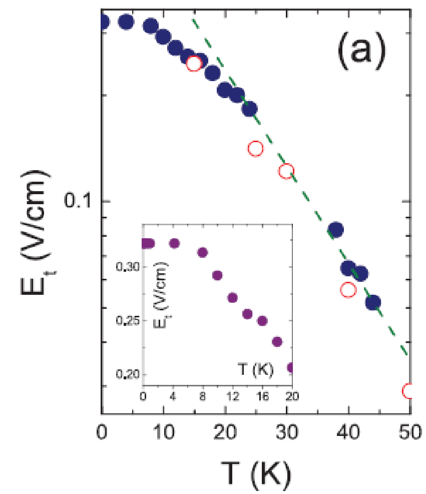
To compare different compounds and samples – effective conductivity: $\sigma^*_{CDW} = j_{CDW}/(E-E_t)$





CDW sliding is possible down to lowest temperature





E_t(T) up to lowest T

CDW conductivity in Hall driven sliding regime is near order of magnitude larger.

→ Important role of interaction the CDW and co-direction normal current

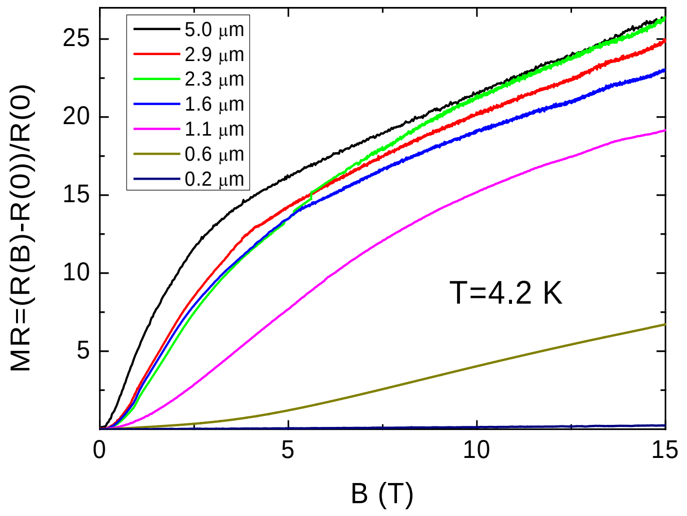
No low temperature problem of sliding

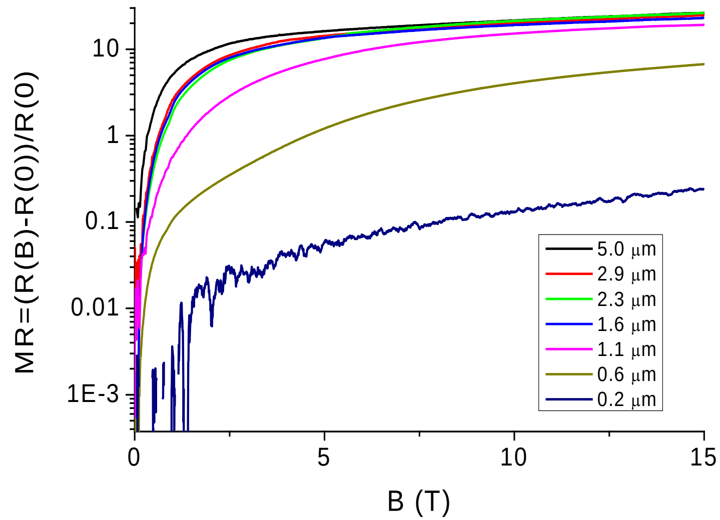
APL. 118, 213102 (2021)

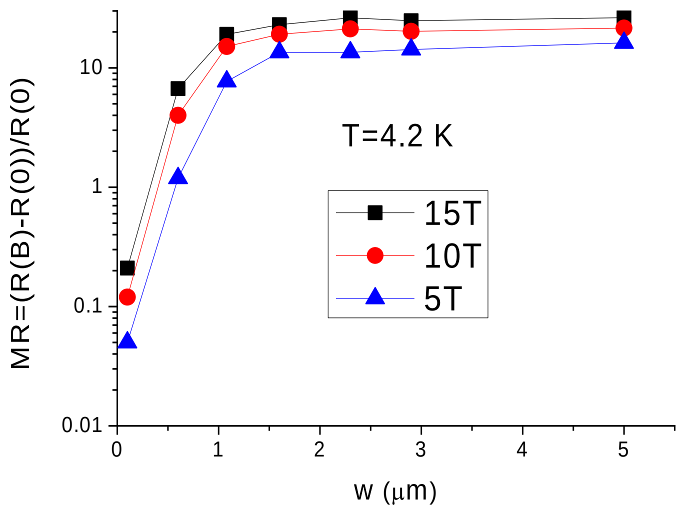
What happens when we are reducing the width of structures (length of the CDW chains)?

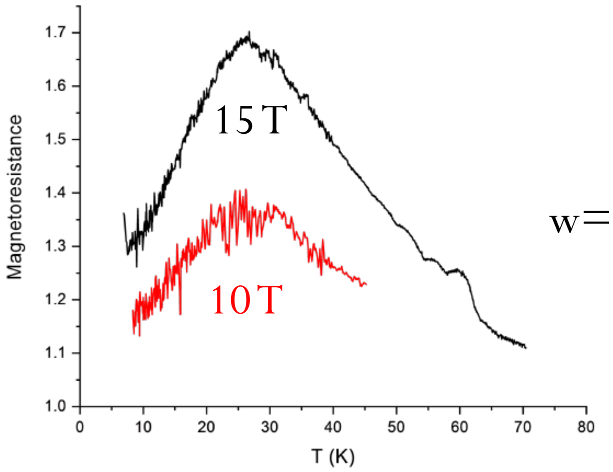
TWO SIZE EFFECTS

1. Strong decrease of magnetoresistance with decrease of w









Similar effect in graphite

PRL **99,** 216601 (2007) PHYSICAL REVIEW LETTERS week ending 23 NOVEMBER 2007

Sample-Size Effects in the Magnetoresistance of Graphite

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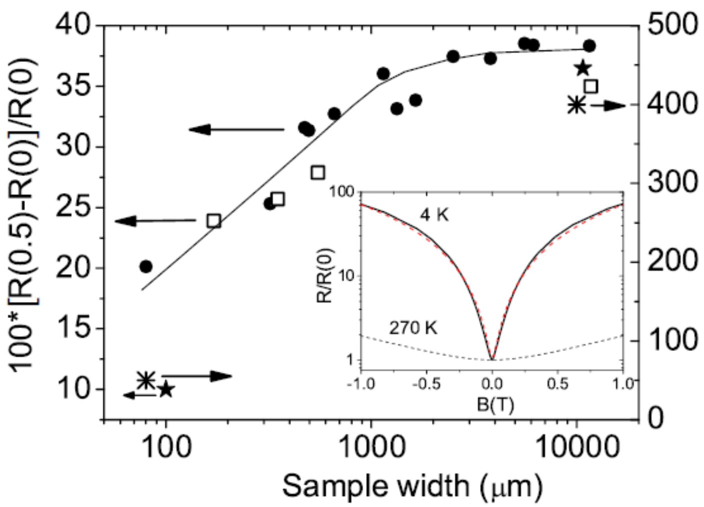
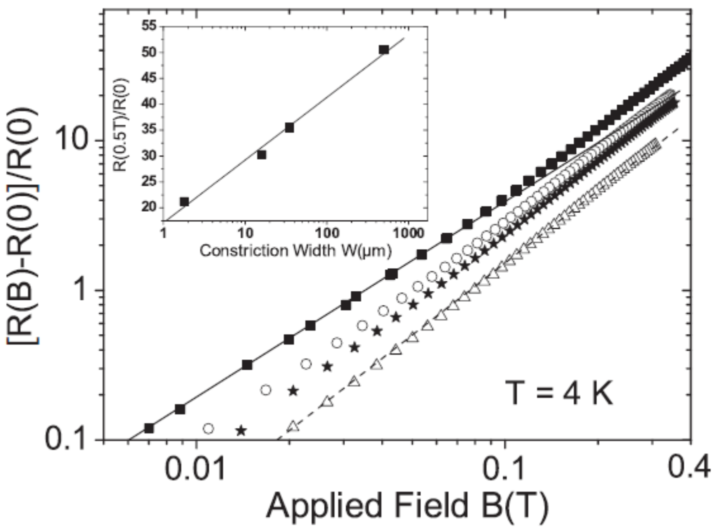
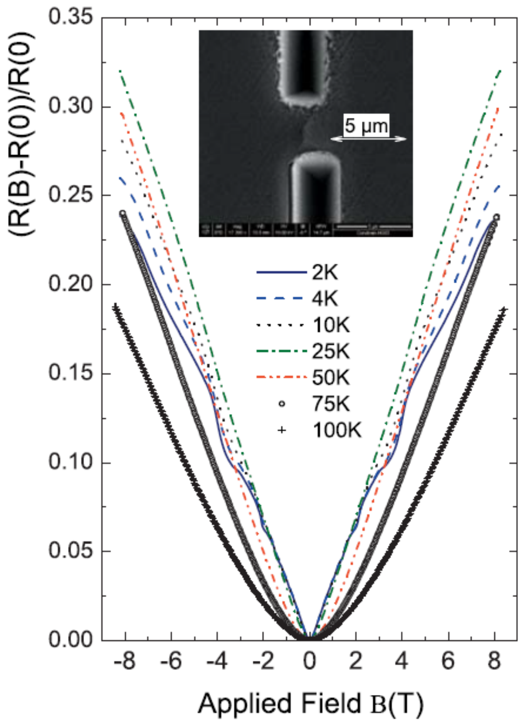
(Received 20 June 2007; published 20 November 2007)



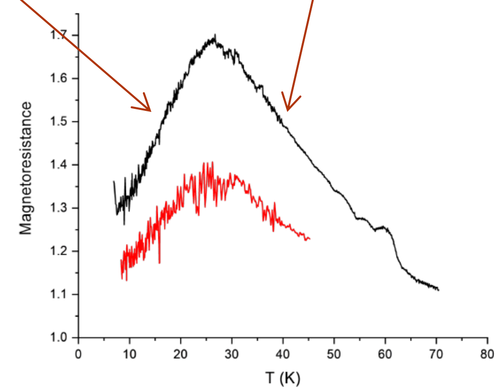


The same T-dependence



MR increases

>30 K MR decreases



"… when the sample size is of the order or smaller than the Fermi wavelength or mean free path, the classical Boltzmann transport theory becomes gradually not valid …"

"… When the mean free path of the electrons is of the order or larger than the platelets size, then electrons reflect and are being transmitted coherently at the borders of the platelets and quantum currents circulate creating Hall-like potentials."

Abrikosov extreme quantum state

A.A. Abrikosov, J.Phys.A (2003); PRB (1998), PRB (1999)

The conditions:

$$n_e \ll \left(\frac{eH}{\hbar c}\right)^{3/2} \qquad T \ll \frac{eH\hbar}{m^* c}$$

At $\Omega\tau \gg 1$ perpendicular to the field resistivity:

$\rho \sim N^{-1}$ Scattering leads increase of conductivity

$NbSe_3$ →

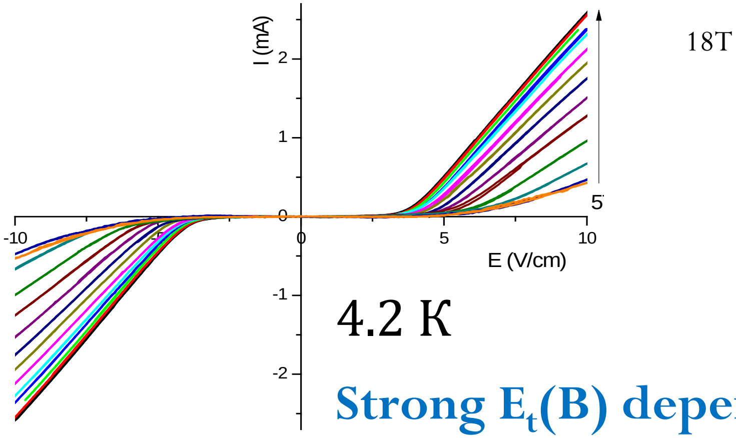
$$\begin{cases} n_{h,e} \approx 10^{18}\, cm^{-3} \\ m^* \approx 10^{-1} m_e \\ \Omega\tau \approx 1 \text{ at } H = 0.03 \text{ T} \end{cases}$$

$$\frac{eB\hbar}{m^* k_B} = 4.2K \quad \text{at } B = 0.31 \text{ T}$$

Estimation of mean free path for $NbSe_3$ at T=4 K, m*= 0.24 and $v_F = 2.7 \times 10^7$ cm/c, and mobility 3×10^5 cm^2/Vc (b-axis), 2×10^4 cm^2/Vc (c-axis) gives ~20 μm b-axis) and ~1.0 μm (c-axis). Drop of MR starts from 1-1.5 μm.

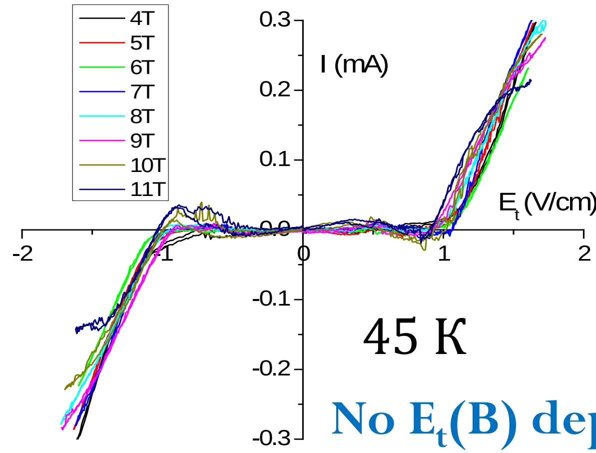
2. Appearance of magnetic field dependence of the threshold electric field for the CDW sliding with decrease of w.

w=0.8 μm



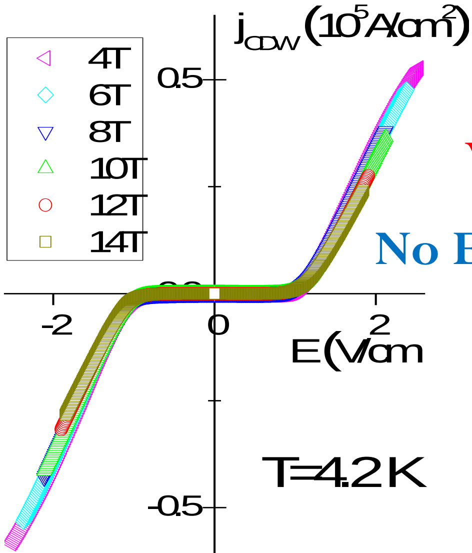
4.2 K

Strong $E_t(B)$ dependence



45 K

No $E_t(B)$ dependence

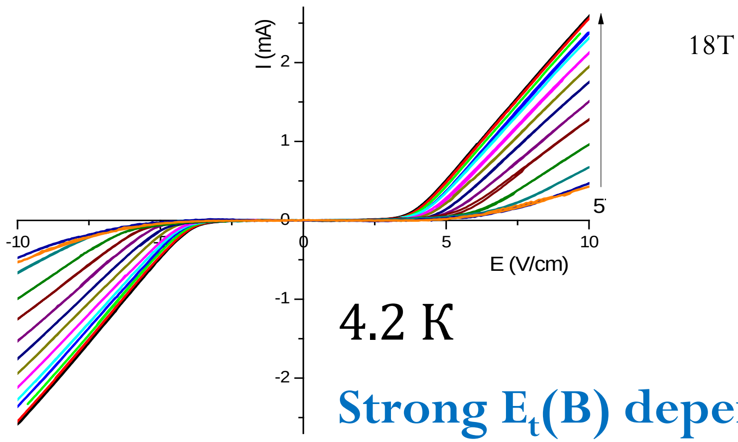


w=5 μm

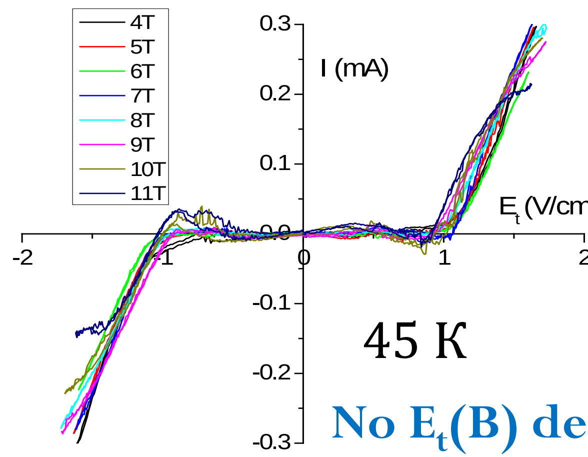
No $E_t(B)$ dependence

2. Appearance of magnetic field dependence of the threshold electric field for the CDW sliding with decrease of w.

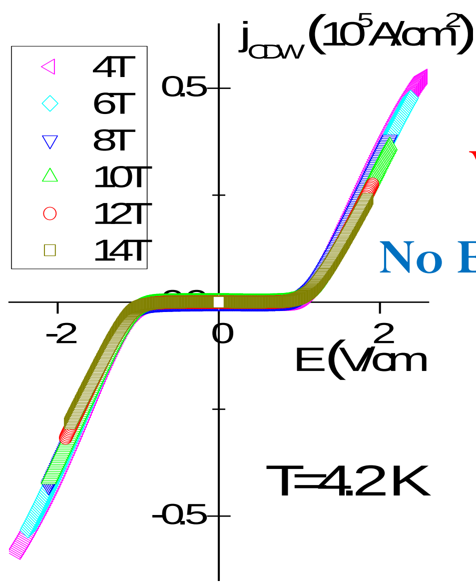
w=0.8 μm



Strong E_t(B) dependence

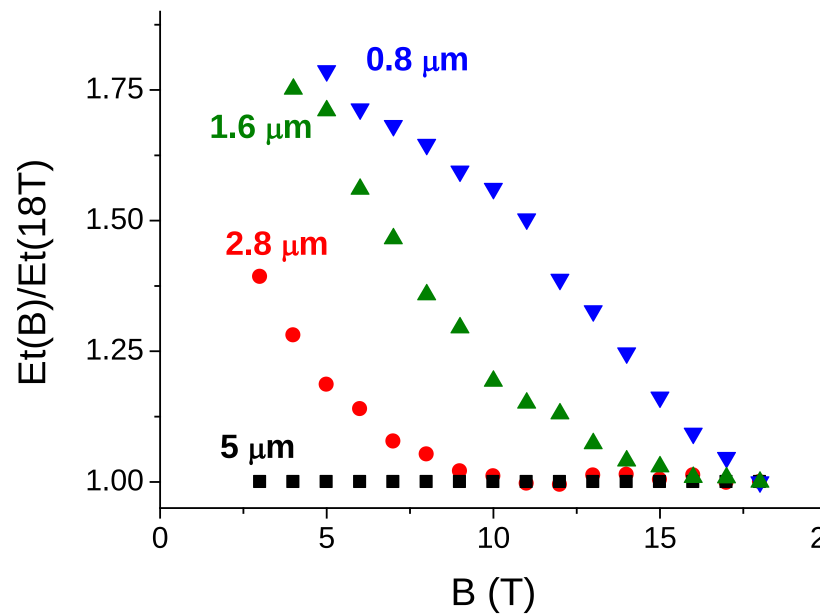


No E_t(B) dependence

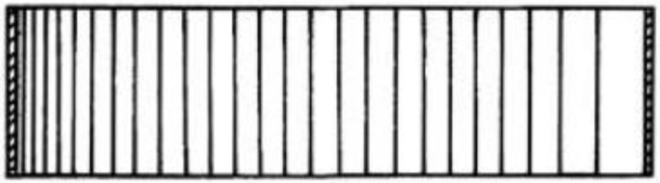


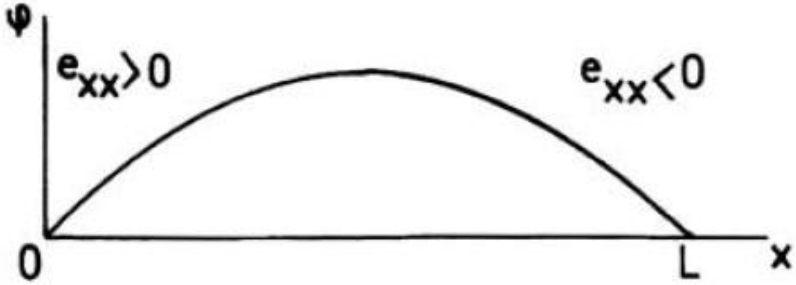
w=5 μm

No E_t(B) dependence



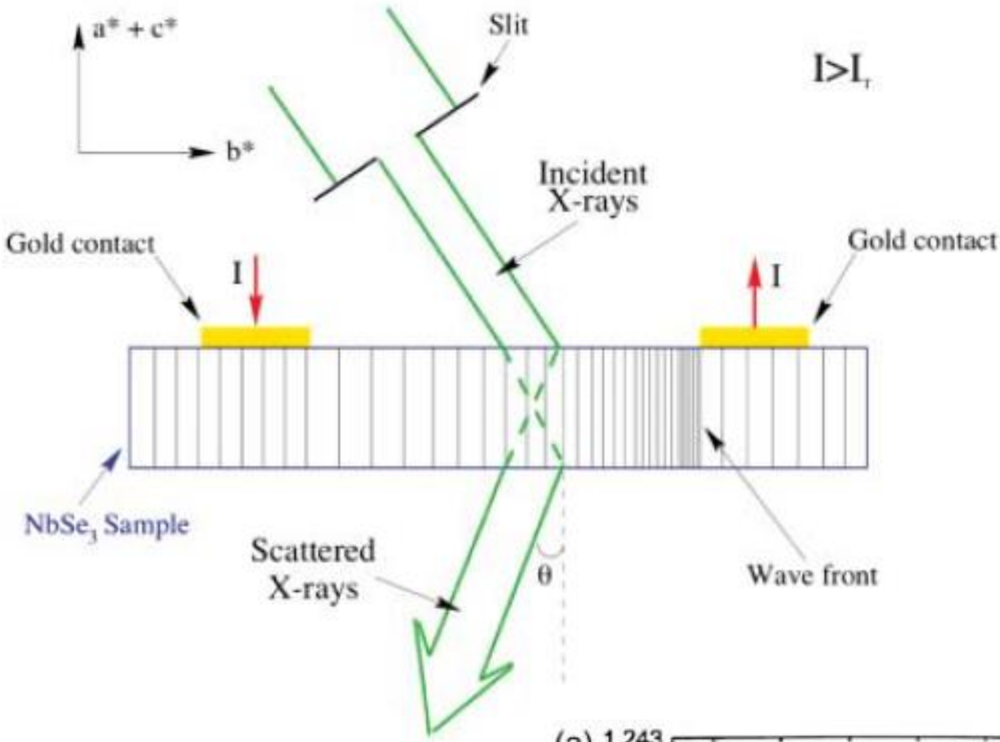
Convention picture





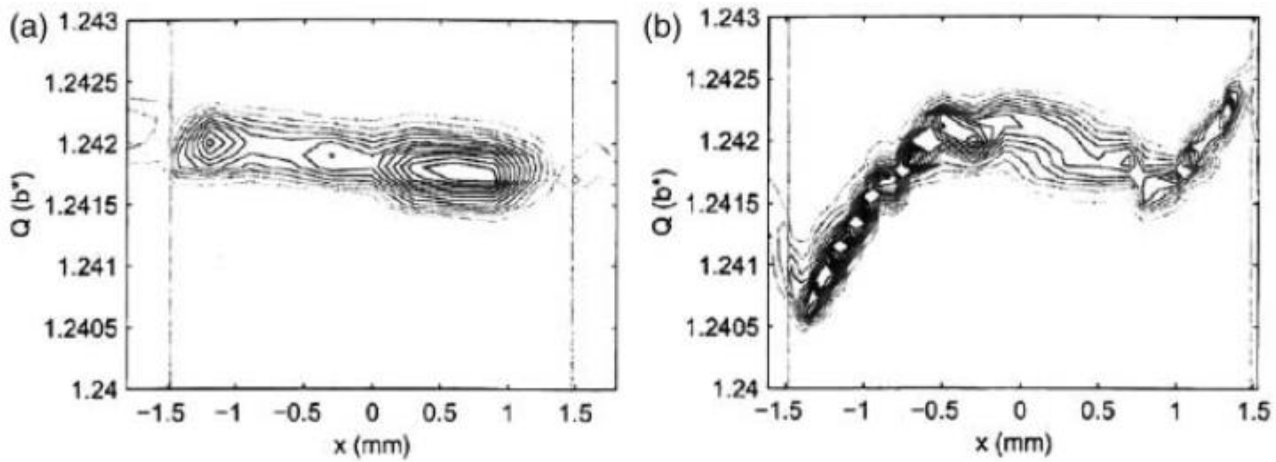
The CDW will start to move when the maximum stress Σ_c at the electrodes will overcome. Σ_c depends on the surface condition, the contact geometry and the nature of CDW–metal interface of the electrode.

Conversion between sliding CDW and strong pinning at the electrodes proceeds through a phase slip (PS). L. Gor`kov (1984)



X-ray spatially resolved studies

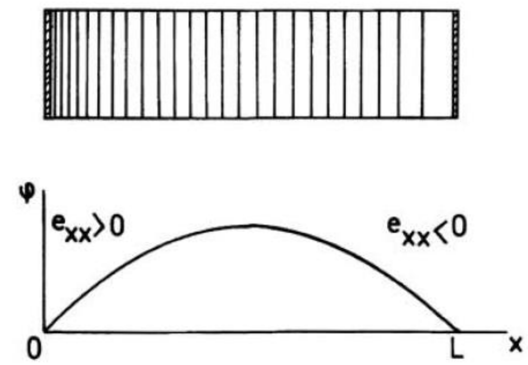
CDW is spatially deformed near contacts on macroscopic scale of order 0.5 mm.



Nucl. Instrum. Meth. Phys. Res. A 467–468 (2001) 1010; Phys. Rev. Lett. 80 (1998) 5631

In our case the length of samples is more than 2 order less than the contact deformation region

In our configuration phase slip needs corresponding CDW edge deformation also . What is the result?

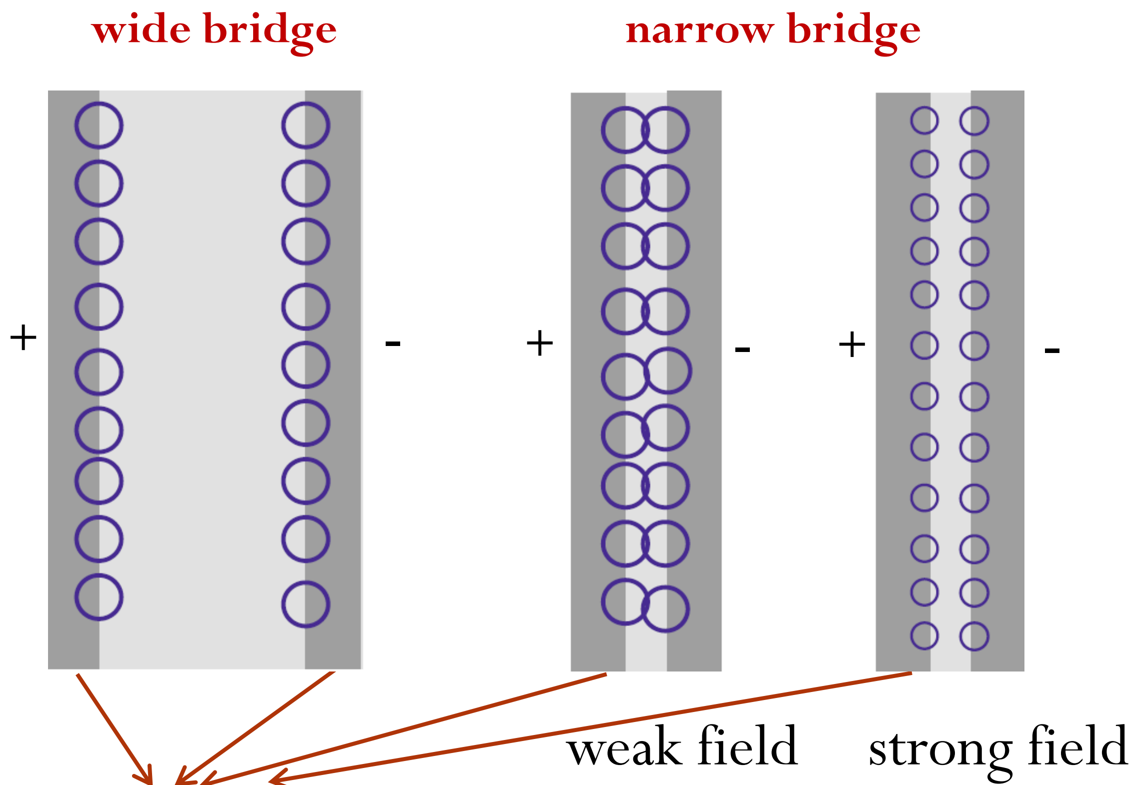


Space deformation of the CDW leads charge excitation

$$d\varphi/dx \longrightarrow \delta q$$

In quantum magnetic field each charge is localized on the Larmor orbit. For $NbSe_3$ R_L=0.4 μm at B= 1 T

Possible explanation



CDW edge deformation

Characteristic size ~ 1.2÷ 1.4 μm

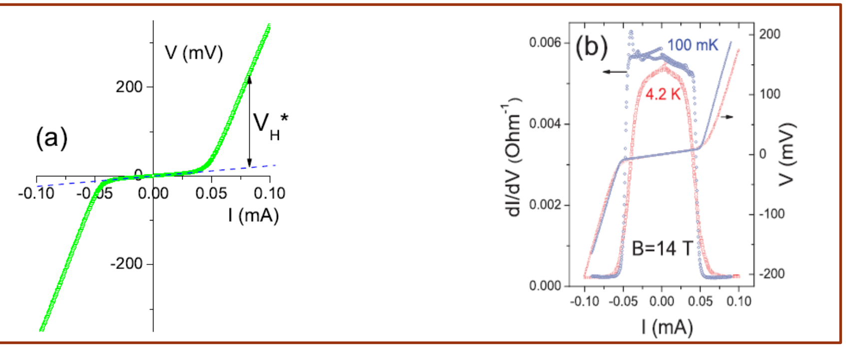
more than 500 times less

What is happening at overlapping of Larmor orbits?

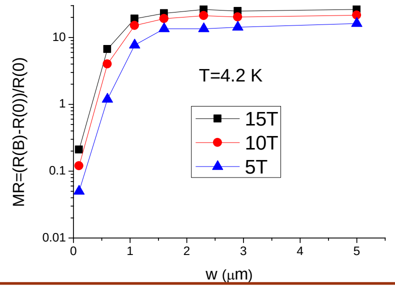
No CDW deformation – No sliding ???

CONCLUSION

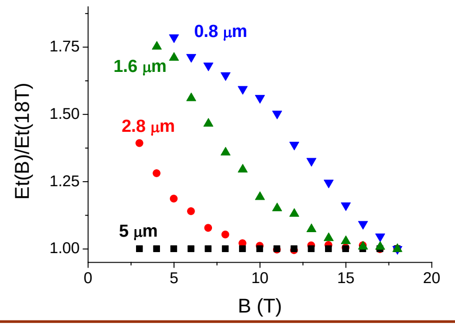
1



2



3



Thank you very much for your attention