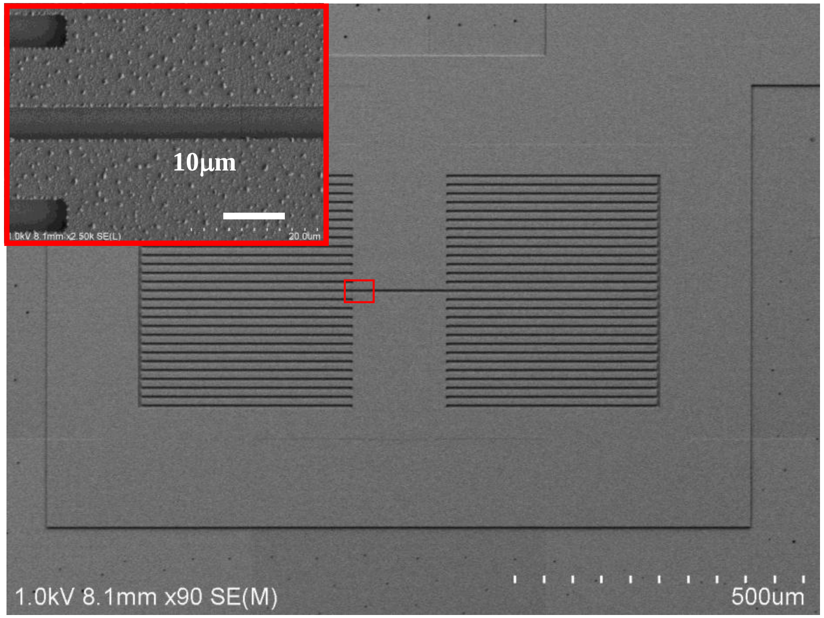
2010. 5. 21 Princeton University

Wigner Crystals
Confined in Micrometer-wide Channels

Hiroki Ikegami
RIKEN, Japan

Collaborators;
Hikota Akimoto
Kimitoshi Kono



Outline

1. Introduction

2. Device

3. Nonlinear transports of a Wigner crystal
   - Bragg-Cherenkov scattering of ripplons
   - decoupling of a Wigner crystal from the dimple lattice

4. Melting of a Wigner crystal in quasi-1D geometry
   - 1D-2D crossover

5. 1.6 μm channel

6. Summary

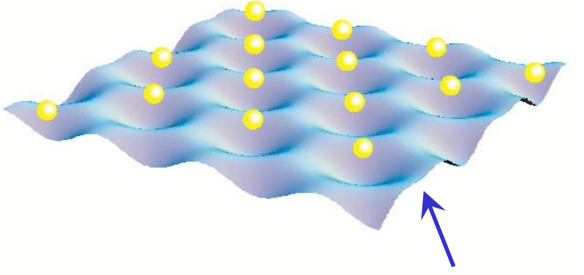
Wigner Crystal

Electrons on helium surface

very low density

density: $10^{11} \sim 10^{13}$ m^{-2}

electron spacing: 0.1 ~ 1 μm



Coulomb repulsion >> kinetic energy

(~93 K @1×10^{13} m^{-2})

⇩

Wigner Crystal coupled with Dimple Lattice

⇩

Unique transport properties of the Wigner crystal

- **Nonlinear transports of a Wigner crystal on superfluid ^{4}He**
  - Bragg-Cherenkov scattering of ripplons
  - decoupling of a Wigner crystal from the dimple lattice

- **Transports of a Wigner crystal on superfluid ^{3}He**
  - resistance caused by the quasiparticle scattering

K. Shirahama et al., PRL 1997, H. Ikegami and K. Kono PRL2006

Outline

1. Introduction

2. Device

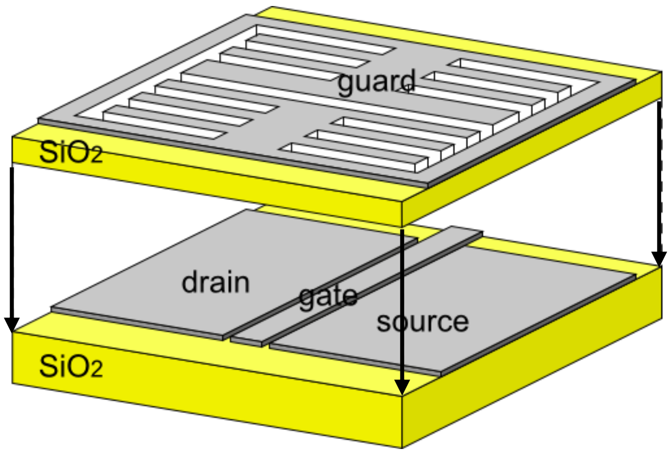
3. Nonlinear transports of a Wigner crystal
   - Bragg-Cherenkov scattering of ripplons
   - decoupling of a Wigner crystal from the dimple lattice

4. Melting of a Wigner crystal in quasi-1D geometry
   - 1D-2D crossover

5. 1.6 μm channel

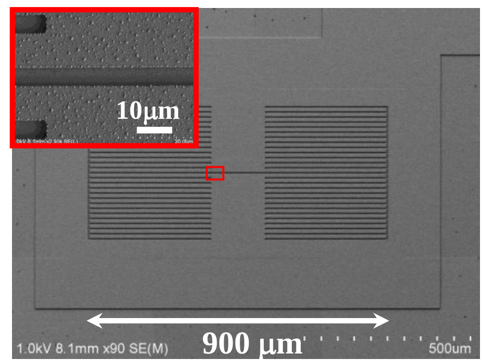
6. Summary

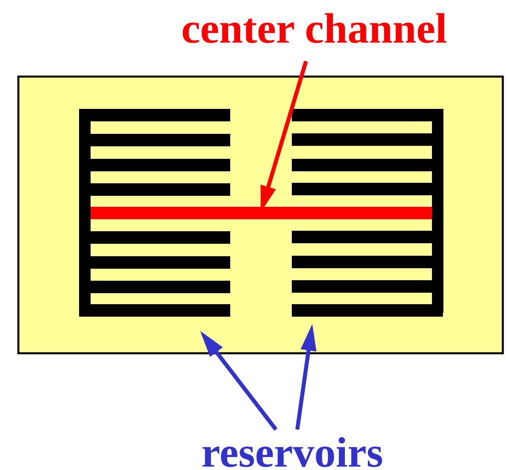
Electrode

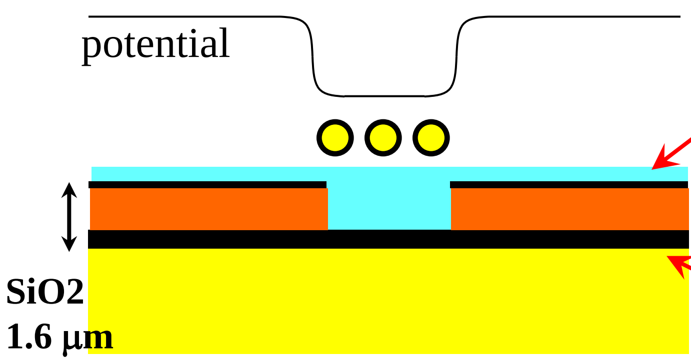


W = 5, 8, 15 μm

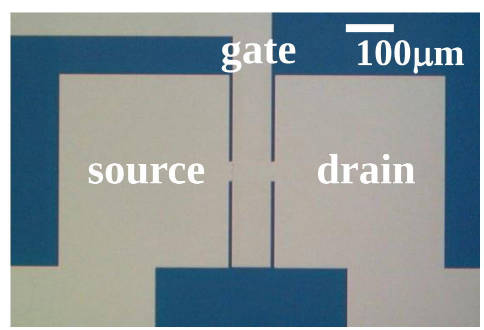
upper electrode (5 μm)



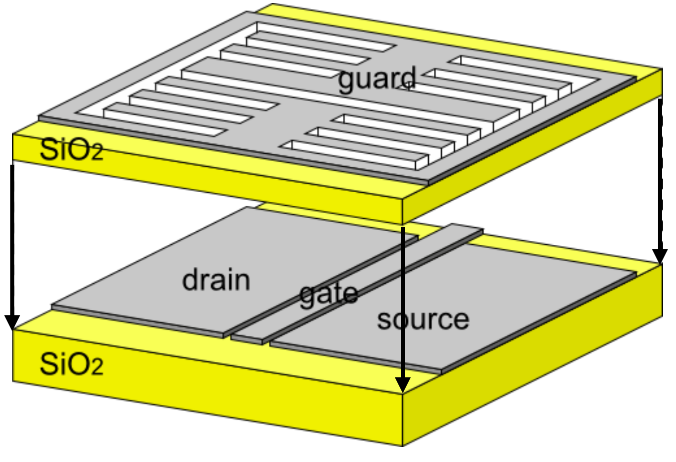


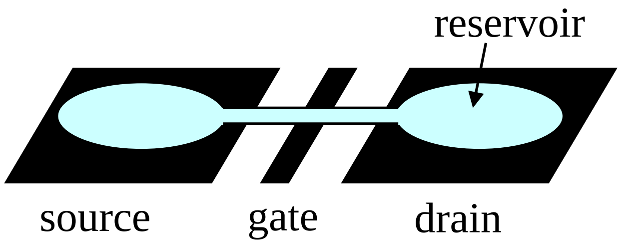


lower electrode

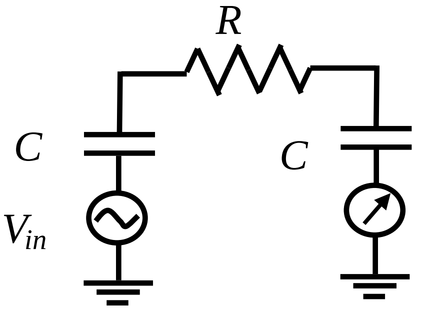


Electrode

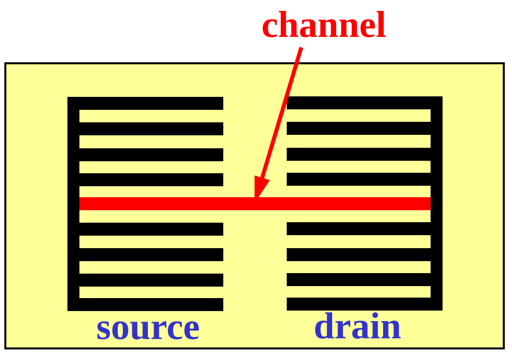


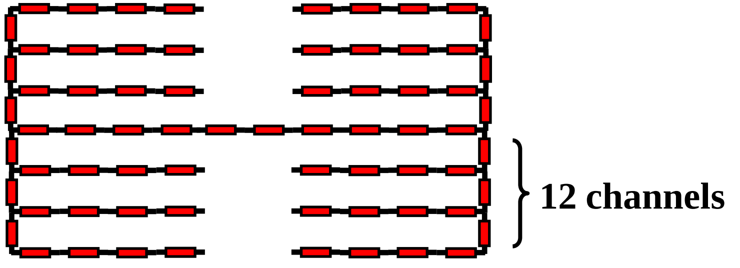


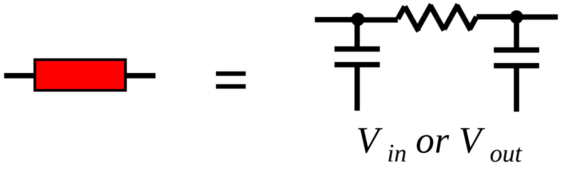
equivalent circuit



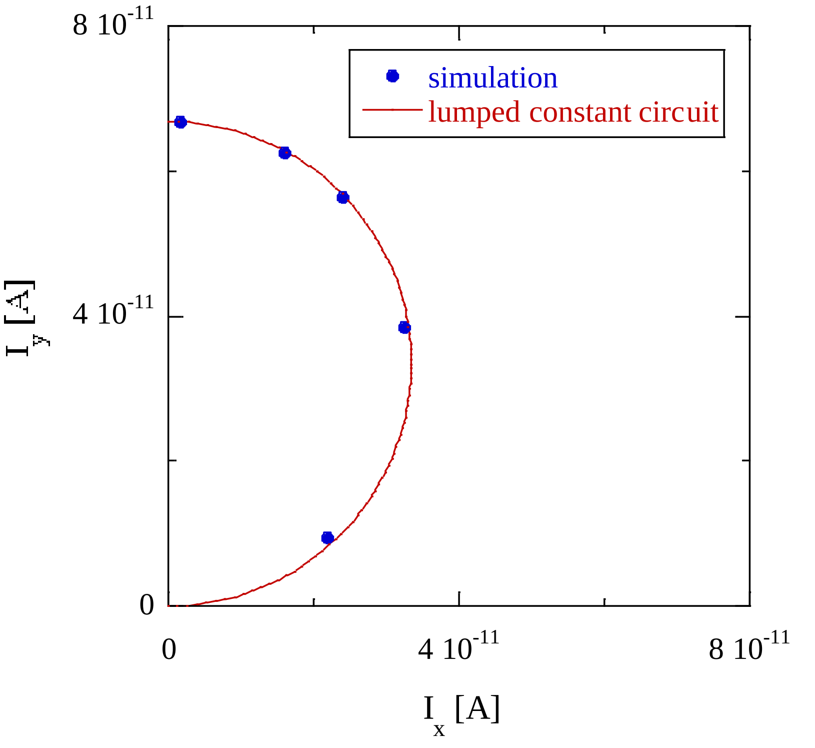
Simulation of Electrode







response of the circuit

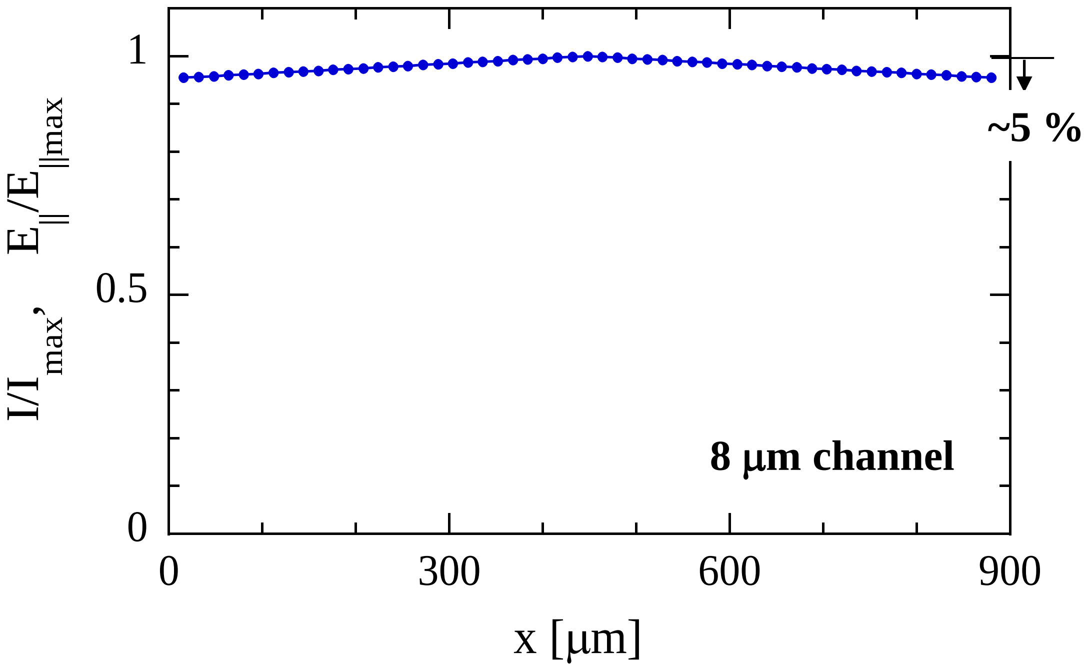


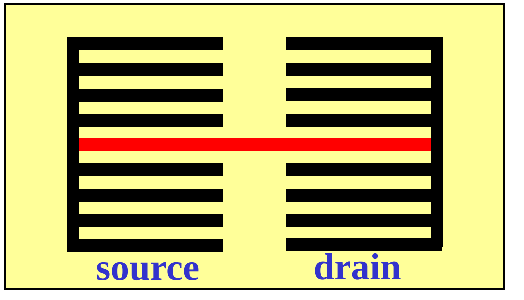
μ= 10, 30, 60, 100, 1000 m^2/Vs

96% of the resistive component comes from the center-channel

Simulation of Electrode

distribution of *I* and $E_{||}$ along the channel

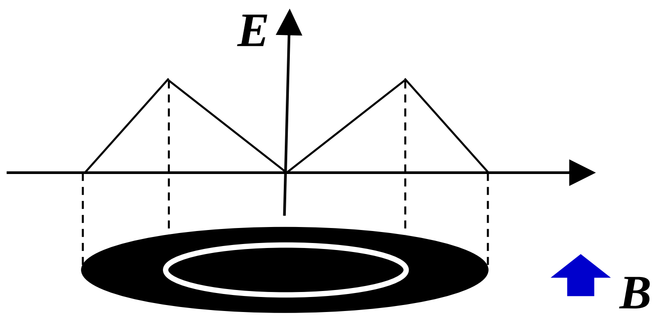




***I* and $E_{||}$ are homogeneous along the channel**

Previous Experiments with Corbino electrode

Current distribution in Corbino geometry



Bragg-Cherenkov scattering

A. Kiristensen *et al*, PRL 77, 1350 ('96).

Decoupling transition

K. Shirahama and K. Kono, PRL 74, 781 ('95).

In nonlinear regime,

distribution of *E* smears the features.

Outline

1. Introduction

2. Device

3. Nonlinear transports of a Wigner crystal
   - Bragg-Cherenkov scattering of ripplons
   - decoupling of a Wigner crystal from the dimple lattice

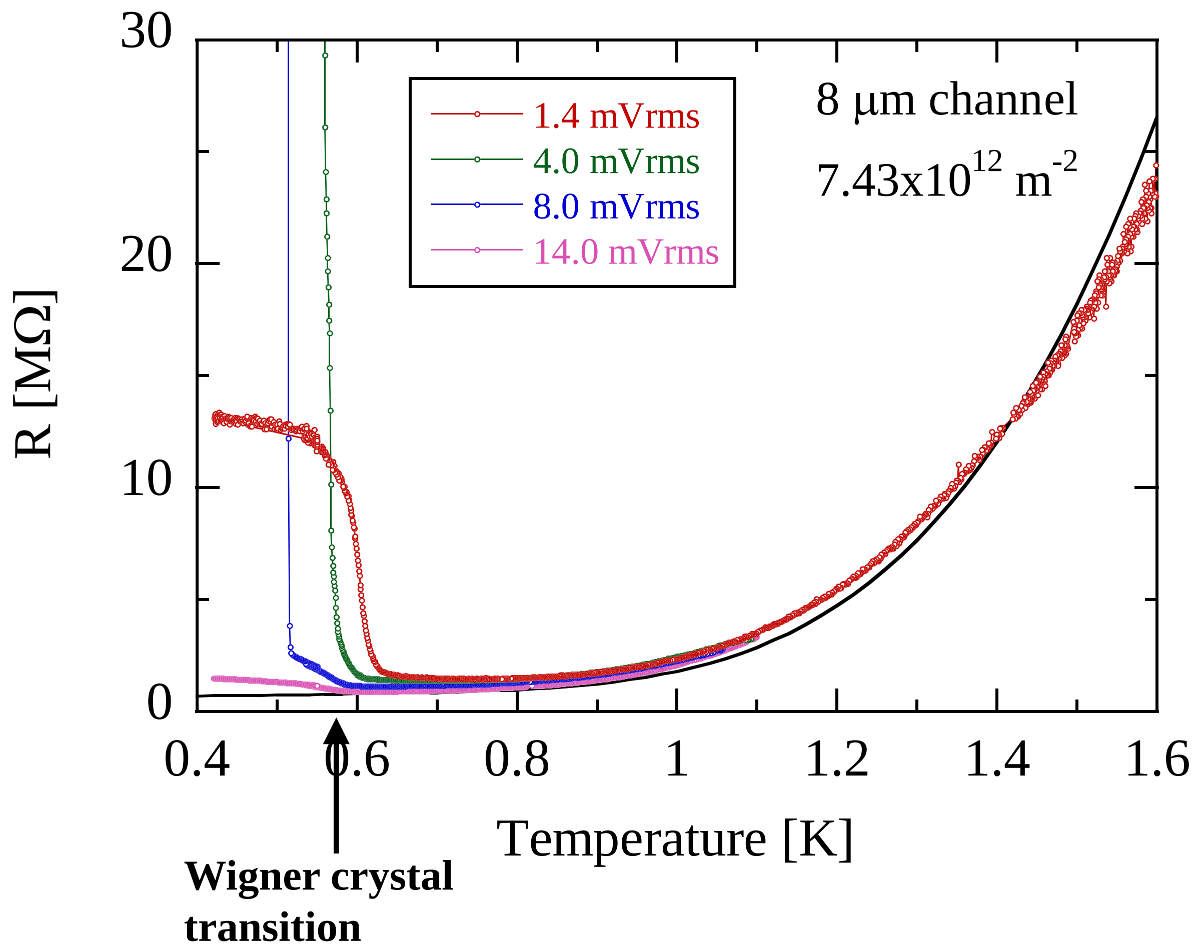
4. Melting of a Wigner crystal in quasi-1D geometry
   - 1D-2D crossover

5. 1.6 μm channel

6. Summary

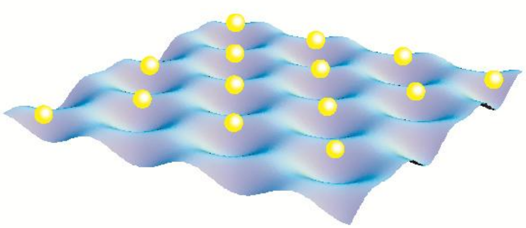
Temperature Dependence of Resistance

8 μm channel



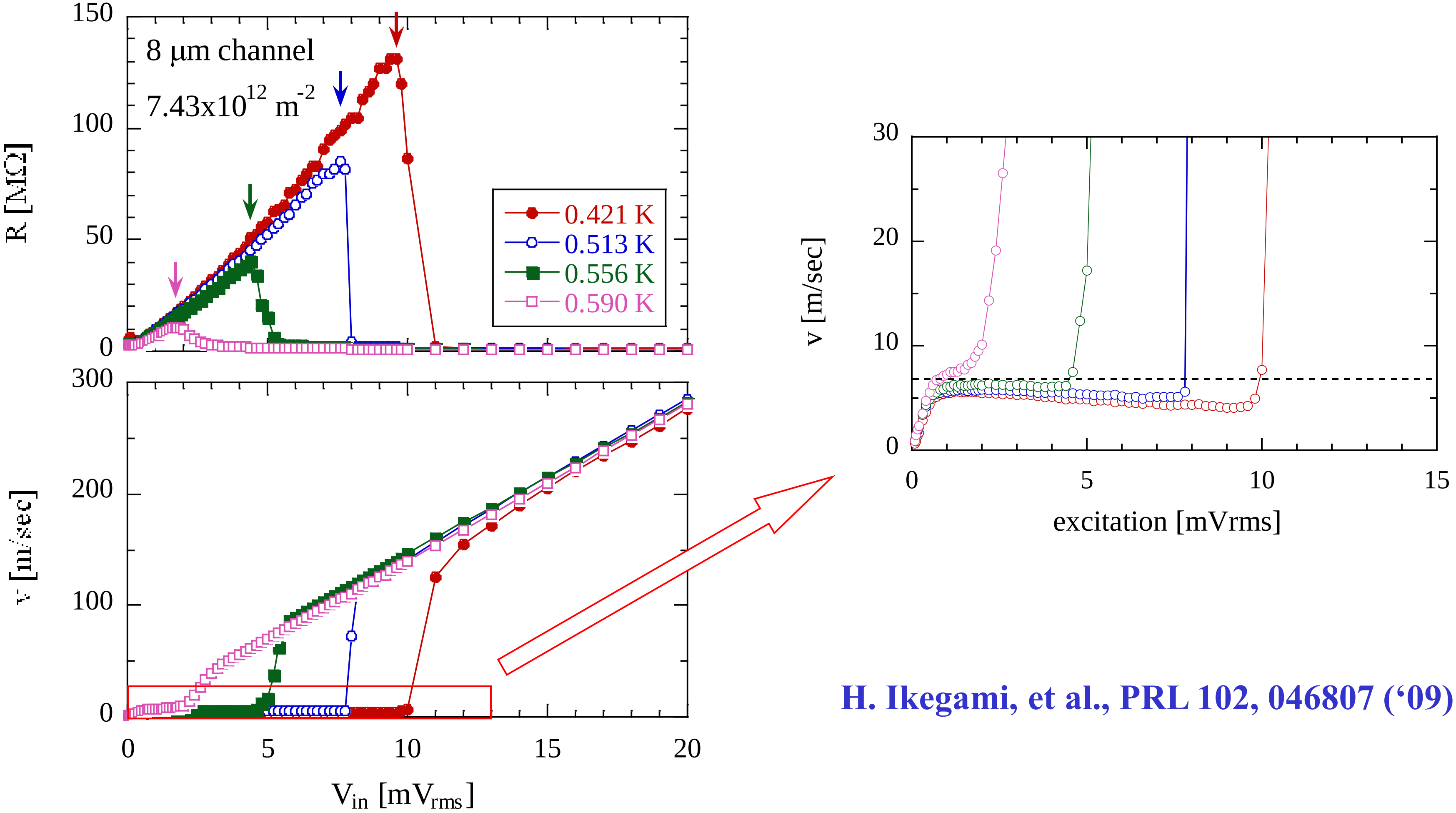
Solid line: Theory,
M. Saitoh JPSJ **42**, 201 (‘77).

Wigner crystal



Strong nonlinear behavior in the Wigner crystal phase

Results: Nonlinear Behavior in Wigner Crystal Phase



H. Ikegami, et al., PRL 102, 046807 (‘09)

- **Electron velocity shows the saturation at low excitations**
- **Velocity jumps to a high value at large excitations**

Bragg-Cherenkov Scattering

Experiment: Kristensen *et al*, PRL **77**, 1350 (‘96).
Theory: Dykman and Rubo, PRL **78**, 4813 (‘97).

Cherenkov emission of ripplon

$$\mathbf{v}\cdot\mathbf{k}=\omega(\mathbf{k})$$

Bragg condition

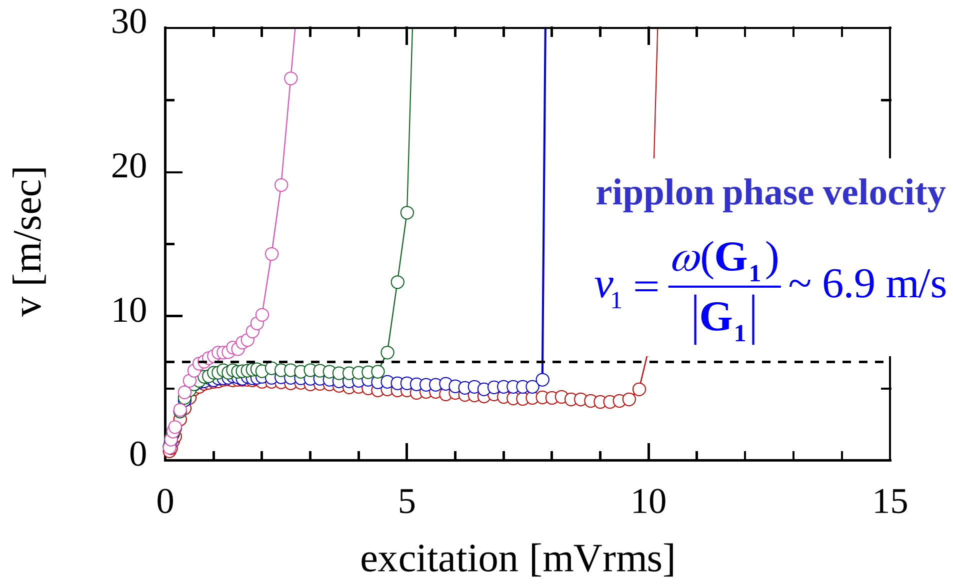
$$\mathbf{k}=\mathbf{G}$$

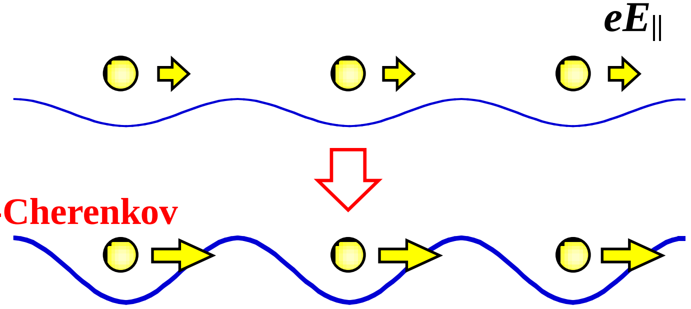
⇩

constructive interference

$$\mathbf{v}\cdot\mathbf{G}=\omega(\mathbf{G})$$

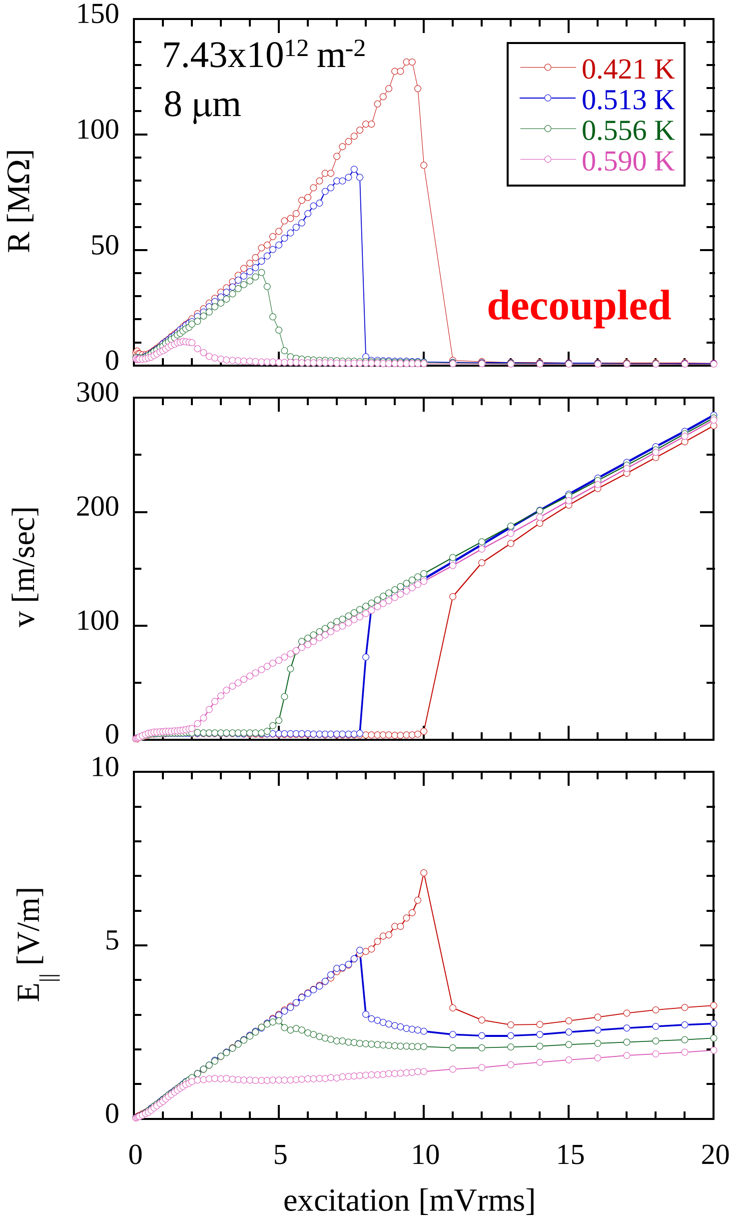
v: velocity of electron
k: wave number of ripplon
ω: energy of ripplon
G: reciprocal lattice vector of Wigner crystal

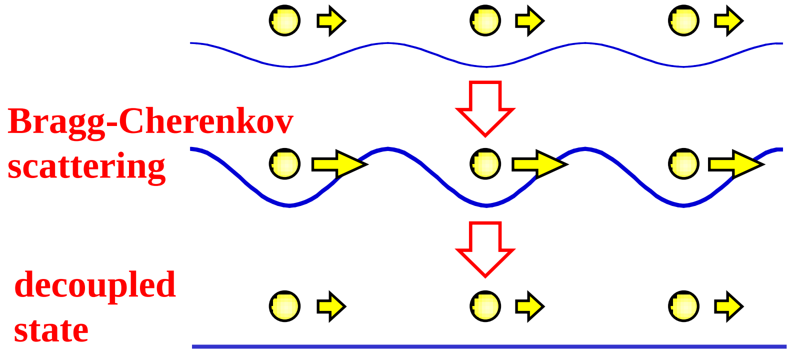




- **Velocity of electrons is limited by the phase-velocity of ripplon**
- **Dimple becomes deeper**

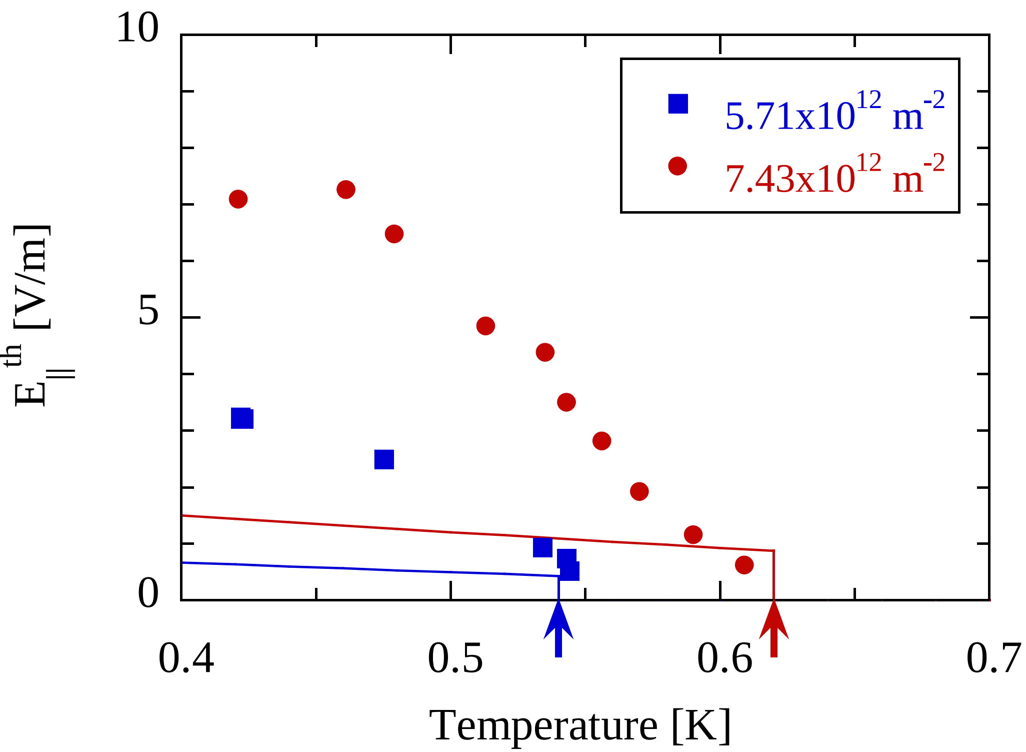
Decoupling of a Wigner Crystal from Dimple Lattice





Decoupling occurs from the Bragg-Cherenkov state

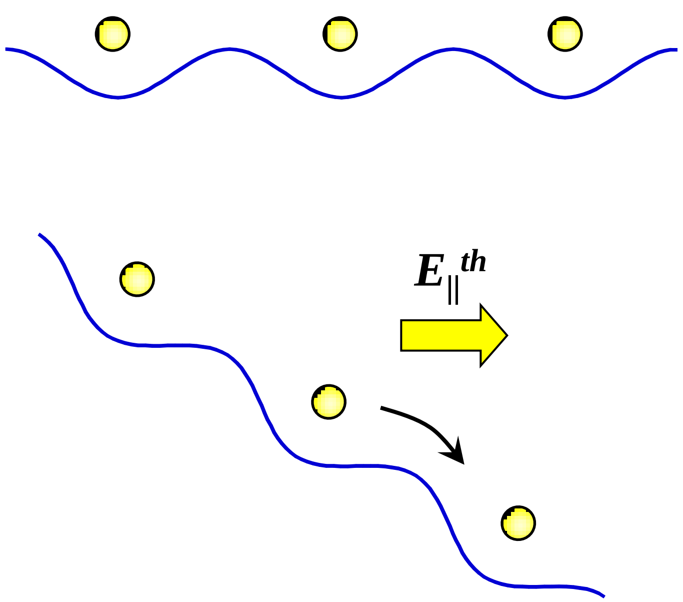
Decoupling of a Wigner Crystal from Dimple Lattice



Decoupling from rigid dimple lattice

K. Shirahama and K. Kono, PRL 1995

Decoupling occurs when the local minimum disappears.



Decoupling from deepened dimple

Outline

1. Introduction

2. Device

3. Nonlinear transports of a Wigner crystal
   - Bragg-Cherenkov scattering of ripplons
   - decoupling of a Wigner crystal from the dimple lattice

4. Melting of a Wigner crystal in quasi-1D geometry
   - 1D-2D crossover

5. 1.6 μm channel

6. Summary

Melting of a Wigner Crystal

In 2D system:
Kosterlitz-Thouless- Halperin-Nelson-Young (KTHNY) mechanism

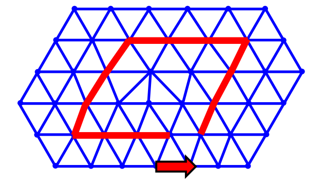
Melting occurs at
plasma parameter $\Gamma = U/K \sim 130$

U: Coulomb interaction
$K = k_B T$: kinetic energy

unbinding of dislocation pairs

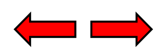
$T > T_m^{2D}$

free dislocation

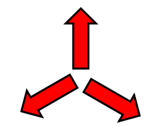


Burgers vector

$T < T_m^{2D}$

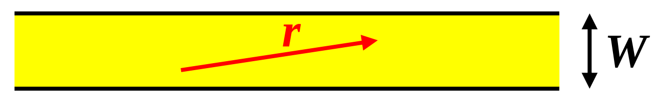


dislocation-pair



three dislocations

In 1D system:
short range order at finite temperature



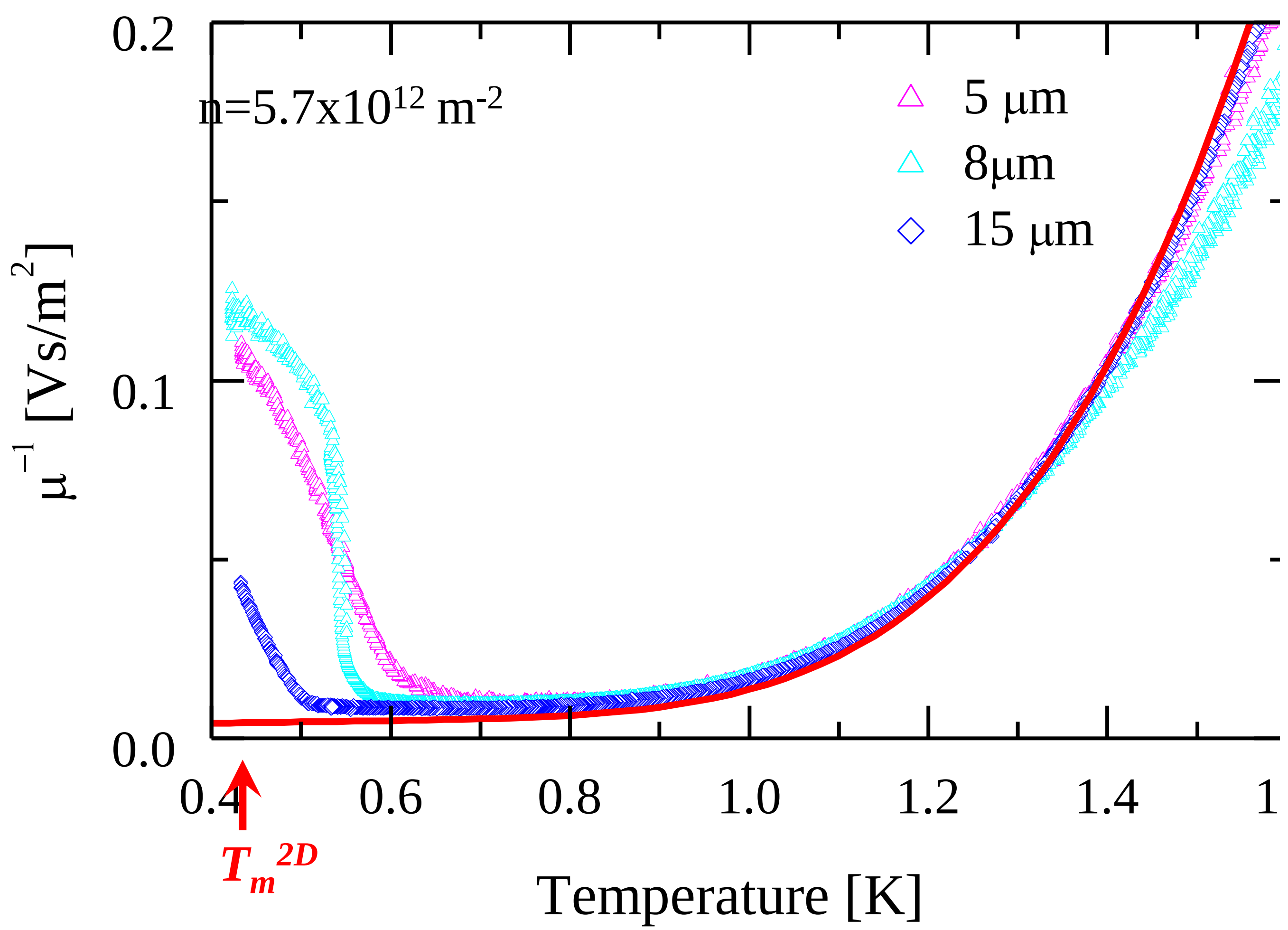
Motivation

How the melting proceeds in the quasi-1D geometry?

⇩

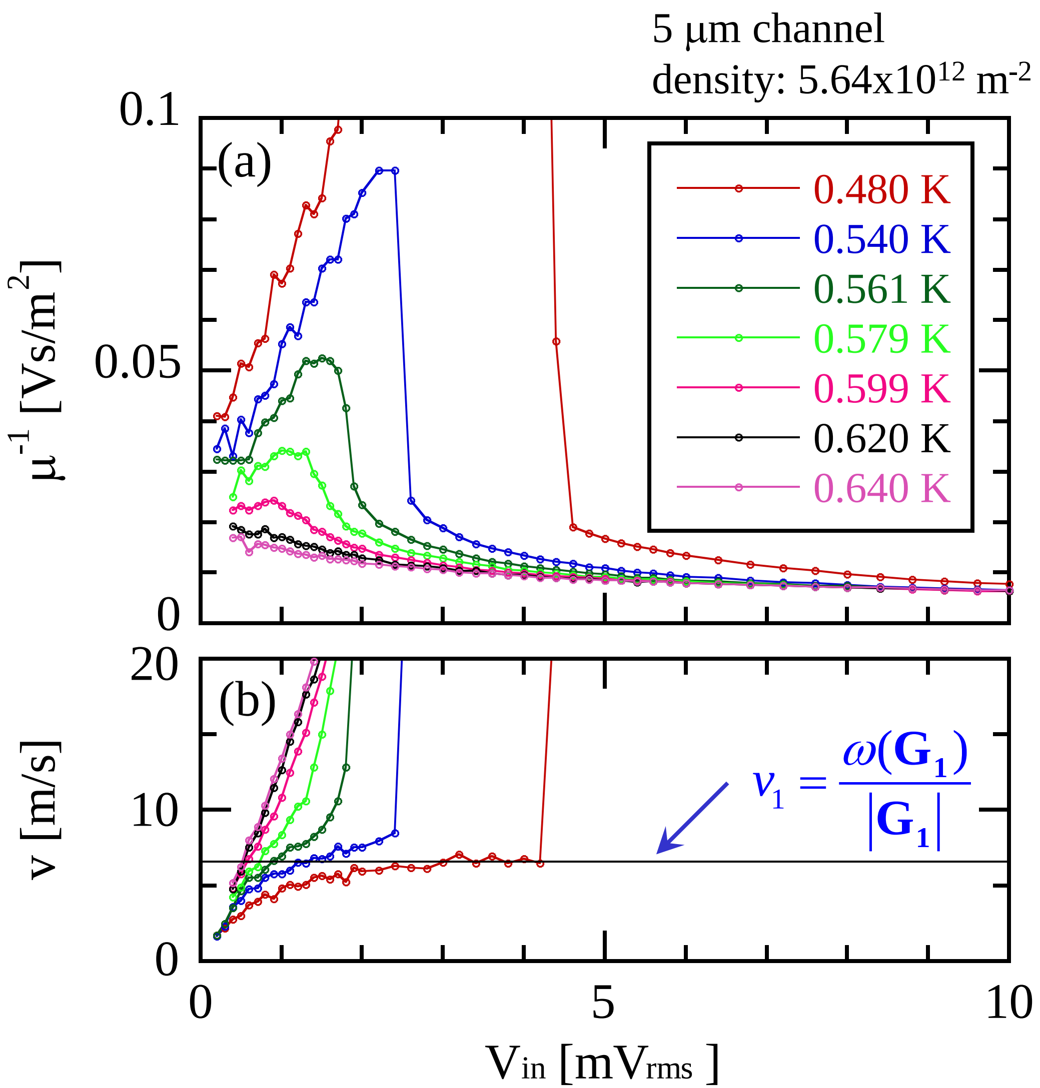
Nonlinear transport measurements of electrons in quasi-1D channels

Temperature Dependence of Mobility



For a narrower channel,
μ^{-1} starts to increase at a higher temperature.

Excitation Dependence of μ^{-1} and v



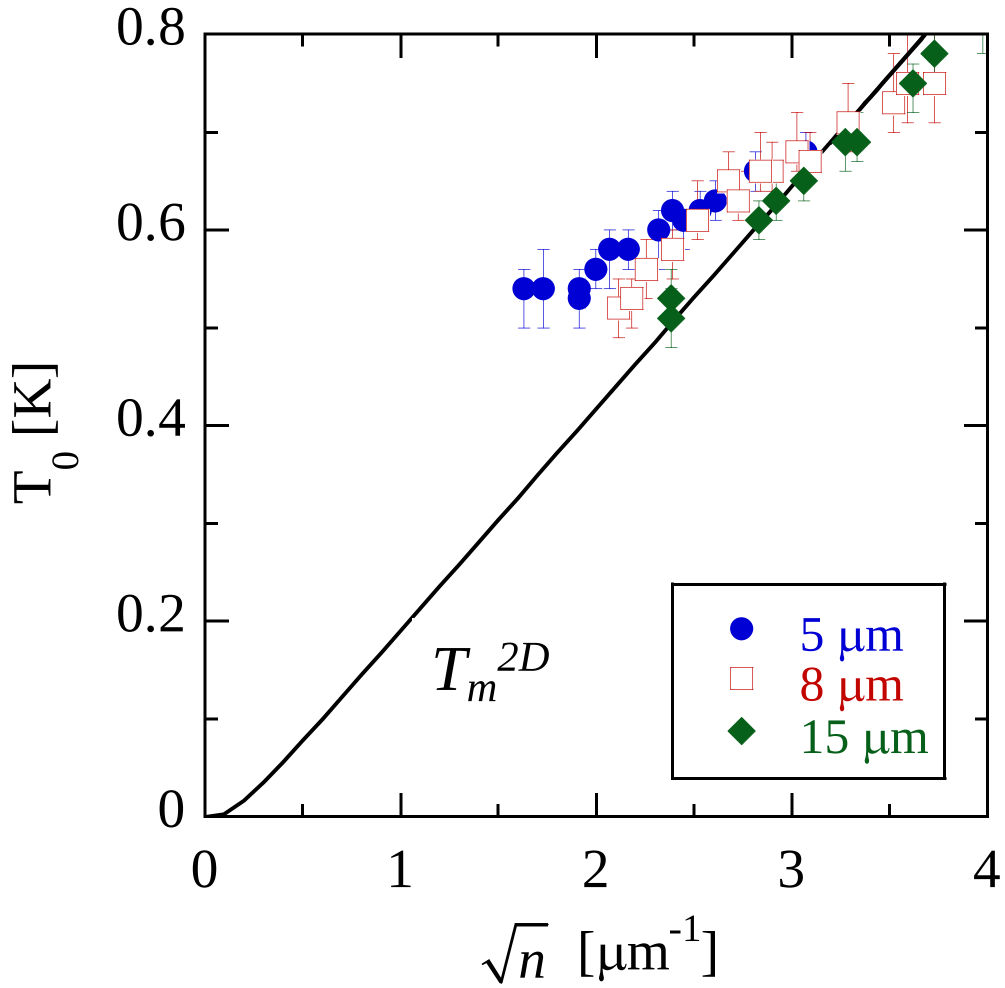
the BC scattering disappears:
***T_0* =0.62 ± 0.02 K**

periodic structure

⇩

Bragg-Cherenkov scattering

Density Dependence of T_0



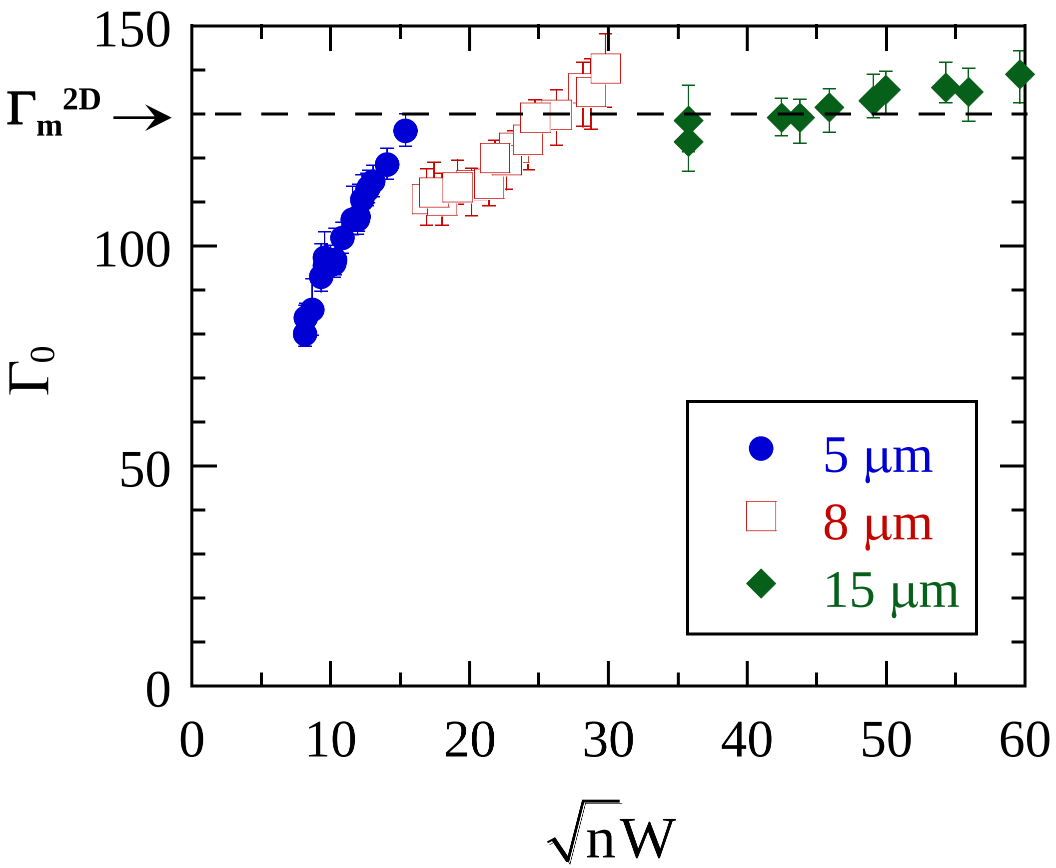
on bulk liquid helium

T_m^{2D}: $\Gamma = U/K \sim 130$

Deviation from the 2D behavior is more significant for a narrower channel and at a lower density.

Γ_0 as a Function of the Number of Electron across Channel

plasma parameter at T_0: $\Gamma_0 = U/k_B T_0$



the plasma parameter at T_0 is smaller for a fewer electrons across the channel

Melting of a Wigner Crystal in 2D

Kosterlitz-Thouless-Halperin-Nelson-Young (KTHNY) mechanism

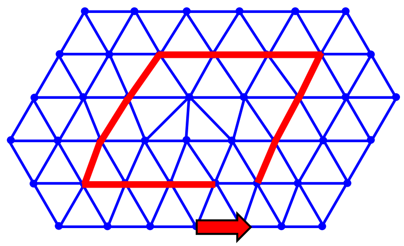
$T<T_m^{2D}$

dislocation-pair   three dislocations

- **positional-correlation function:**
  $\Psi \sim r^{-\eta}$ due to phonons
- **quasi-long range order**

$T>T_m^{2D}$

free dislocation



Burgers vector

- **positional-correlation function:**
  $\Psi \sim \exp(-r/\xi_+)$ due to free dislocations
- **short range order**

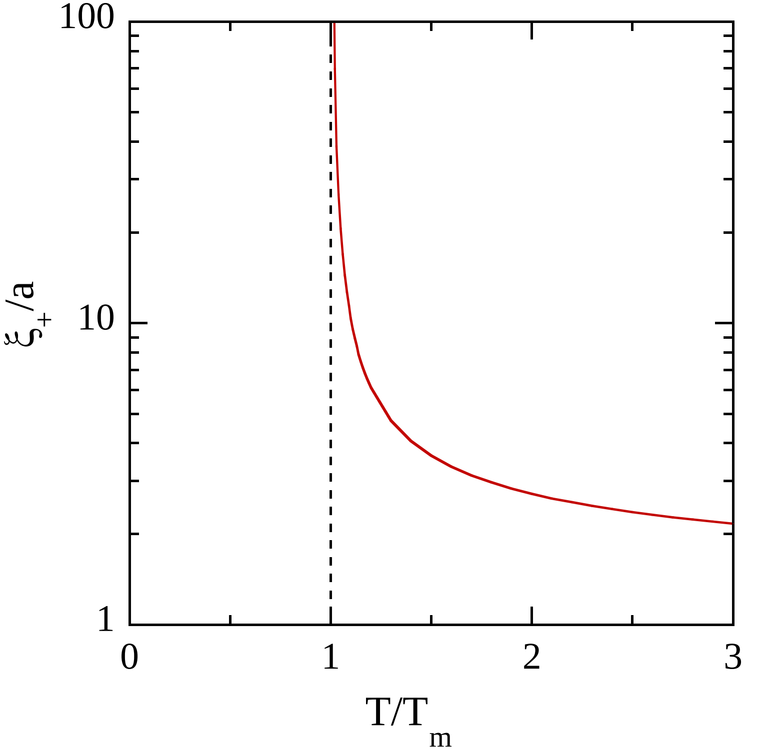
correlation length

(mean distance between dislocations)

$$\xi_+ = A a_0 \exp\left[\frac{b}{(T/T_m^{2D}-1)^{\nu}}\right]$$

a_0: core size of a dislocation

ν=0.36963

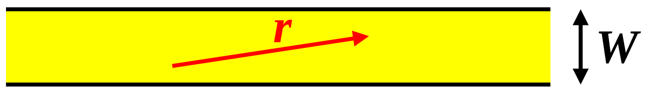


Melting of a Wigner Crystal in quasi-1D Geometry

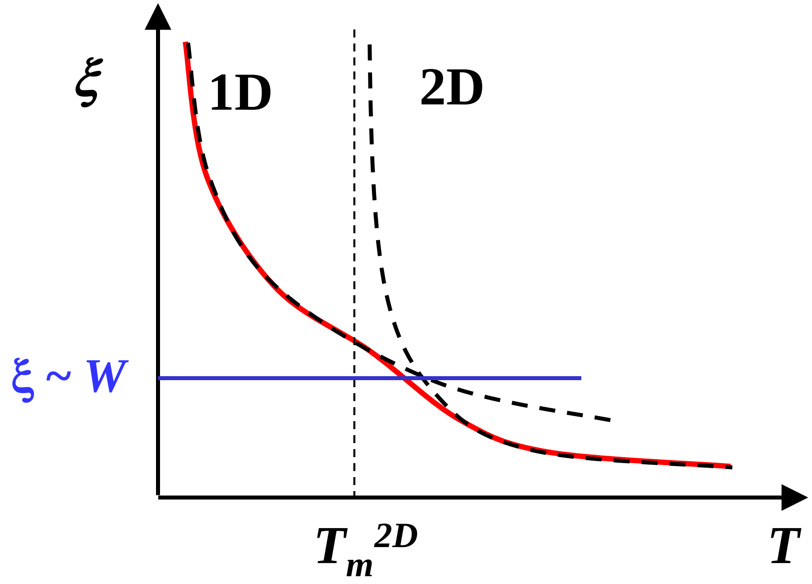
Positional Correlation in quasi-1D geometry

$r > W$: $\Psi \sim \exp(-r/\xi)$ (1D-like)

Short range order
correlation length: $\xi \sim T^{-1}$



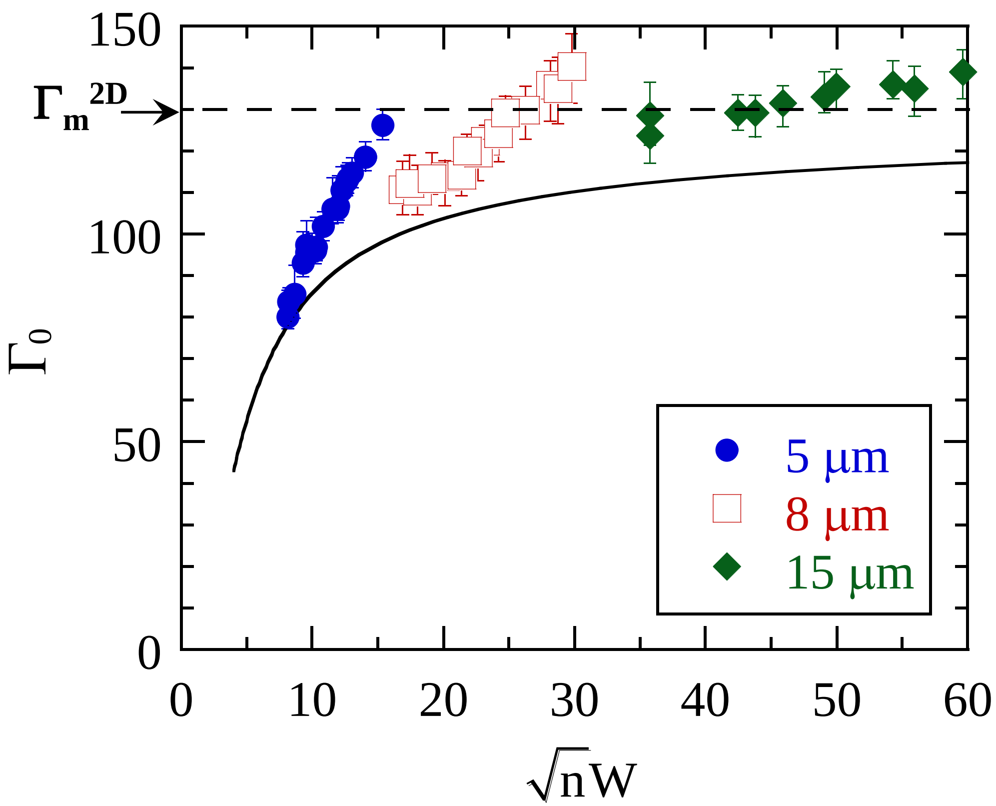
$r < W$: 2D-like



$\xi \sim W$: 1D-2D crossover

Γ_0 as a Function of the Number of Electron across Channel

plasma parameter at T_0: $\Gamma_0 = U/k_B T_0$



solid line: $\xi_+ = W$

$$\xi_+ = A a_0 \exp\left[\frac{b}{(T/T_m^{2D}-1)^{\nu}}\right]$$

$$= A a_0 \exp\left[\frac{b}{(\Gamma_m^{2D}/\Gamma-1)^{\nu}}\right]$$

a_0: lattice constant ( )

ν=0.36963

b=1.8 for $E_c/k_B T_m$=4.9

(numerical calculation

by Fisher, et al, PRB **20**, 4692 (‘79))

A=1.0, Γ_m^{2D}=130

Emergence of free dislocations in the channel causes the disappearance of the Bragg-Cherenkov scattering

Outline

1. Introduction

2. Device

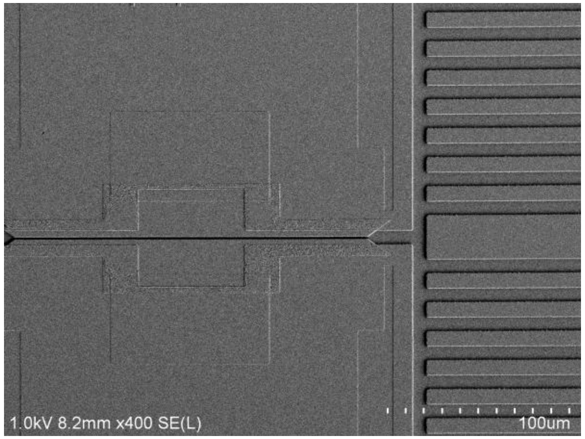
3. Nonlinear transports of a Wigner crystal
   - Bragg-Cherenkov scattering of ripplons
   - decoupling of a Wigner crystal from the dimple lattice

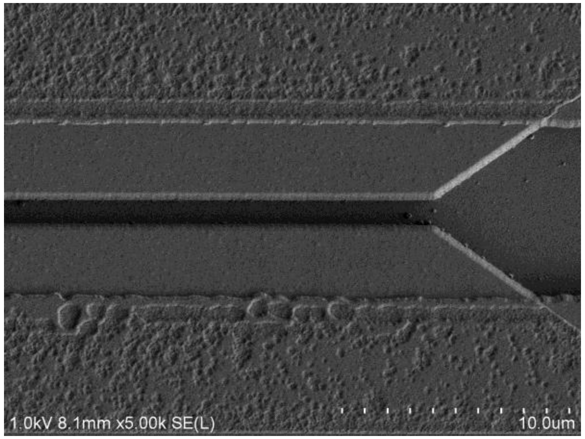
4. Melting of a Wigner crystal in quasi-1D geometry
   - 1D-2D crossover

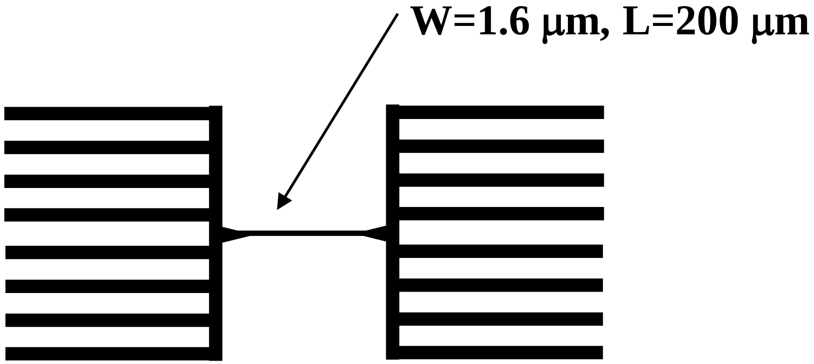
5. 1.6 μm channel

6. Summary

1.6 μm Channel

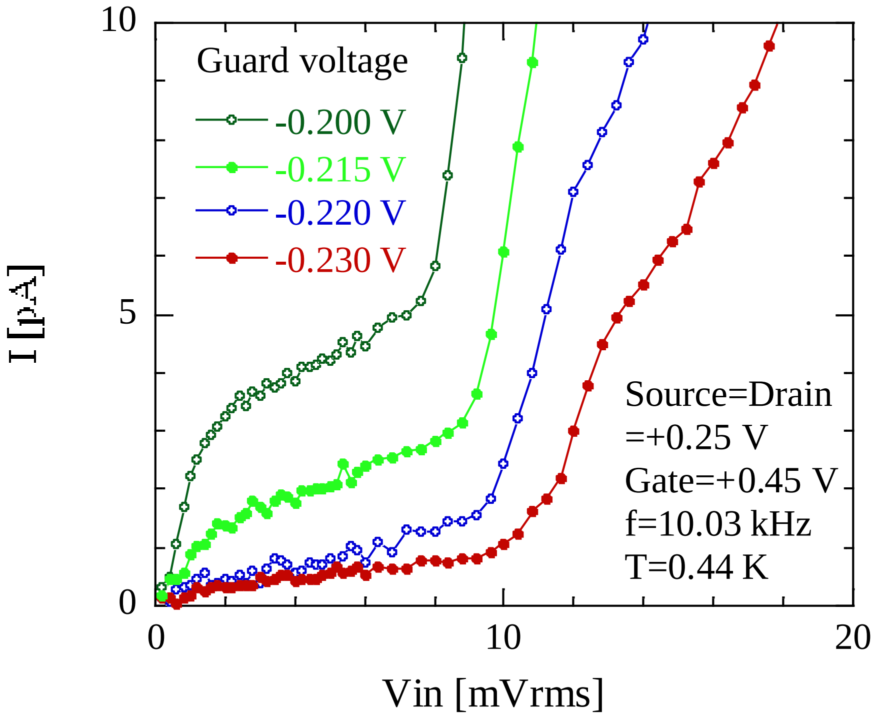


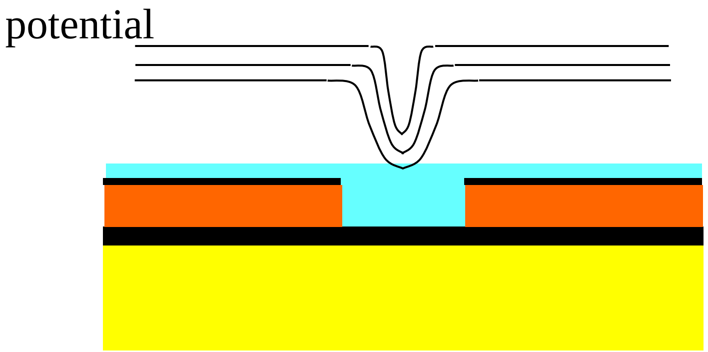




Nonlinear Transport in 1.6 μm Channel

Current as a function of excitation

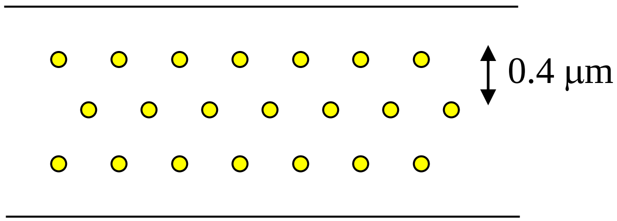




$I=enWv_1$

For three rows of electrons,

I=5.3 pA



the Bragg-Cherenkov scattering occurs in the 1.6 μm-channel

Summary

We have investigated nonlinear transports of Wigner crystals in the quasi-1D geometry.

Nonlinear behaviors

- **Electron velocity is limited by the Bragg-Cherenkov scattering of ripplons.**
- **Mobility jumps at a large excitation due to the decoupling of the Wigner crystal from the dimple lattice.**
- **The decoupling tales place from the deepened dimple lattice.**

Melting of a Wigner crystal in quasi-1D geometry

The nonlinear behaviors disappear at a higher temperature for a fewer electrons across the channel.

- **disappearance of the lattice structure**
- **caused by the emergence of free dislocations in the channel**