Nonlinear transport of Wigner crystal on liquid helium in microchannel devices

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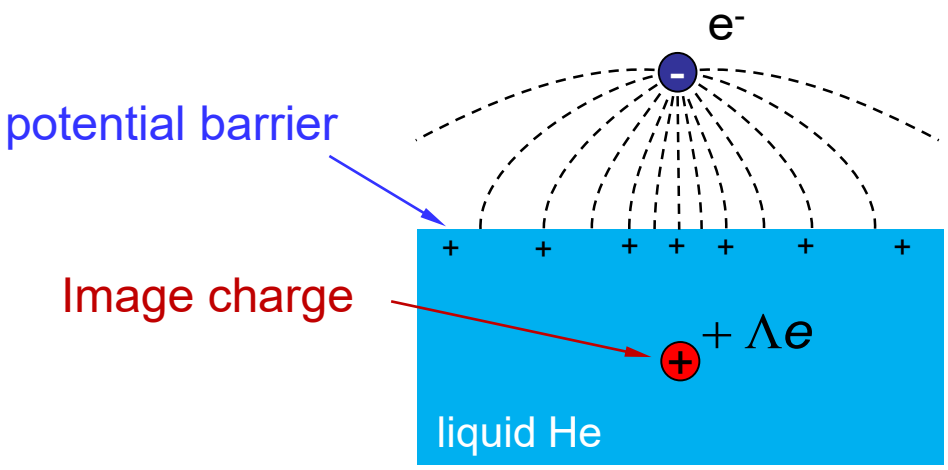
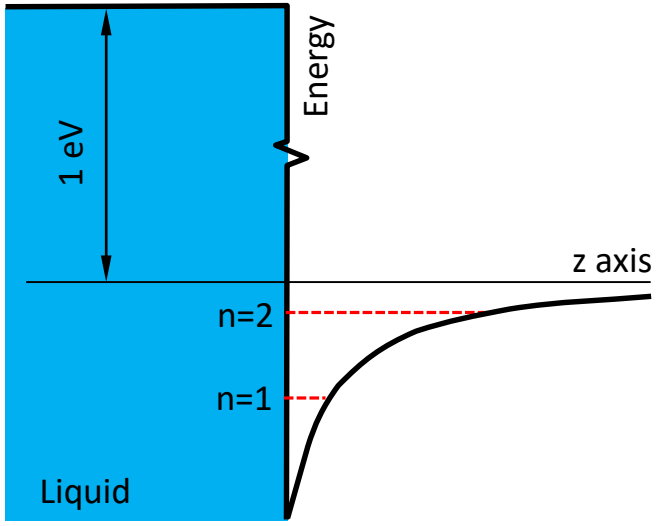
Surface States of Electrons on Helium

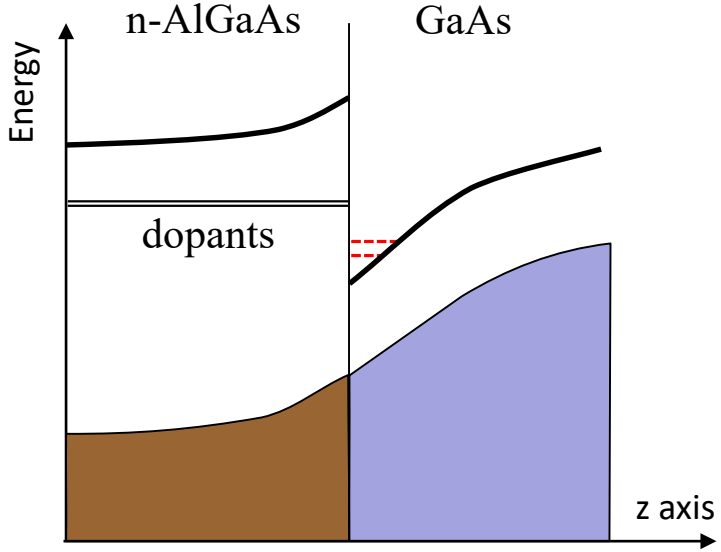




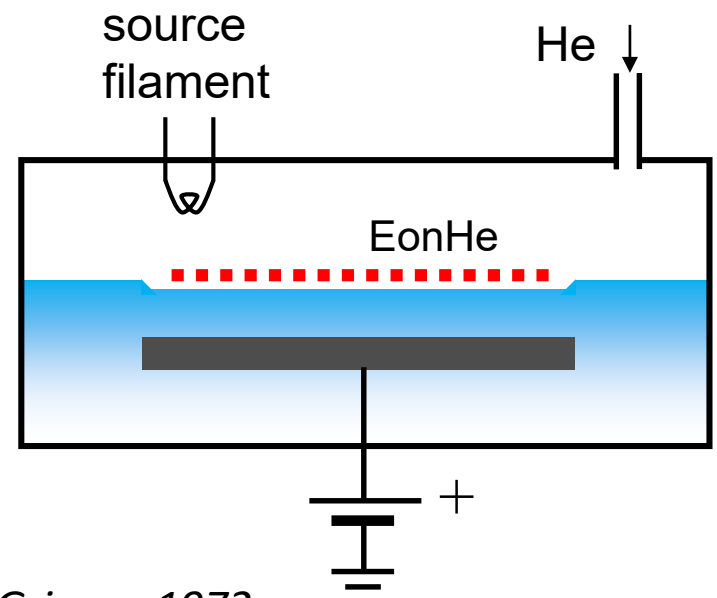
Weak image potential: $$V = \frac{(\varepsilon - 1)}{4(\varepsilon + 1)}\left(\frac{e^2}{z}\right) < 0.01 \times \left(\frac{e^2}{z}\right)$$

Small Rydberg energy: $$R_y = \frac{m\Lambda^2 e^2}{2\hbar^2} \approx 1\,\text{meV} = 10\,\text{K}$$

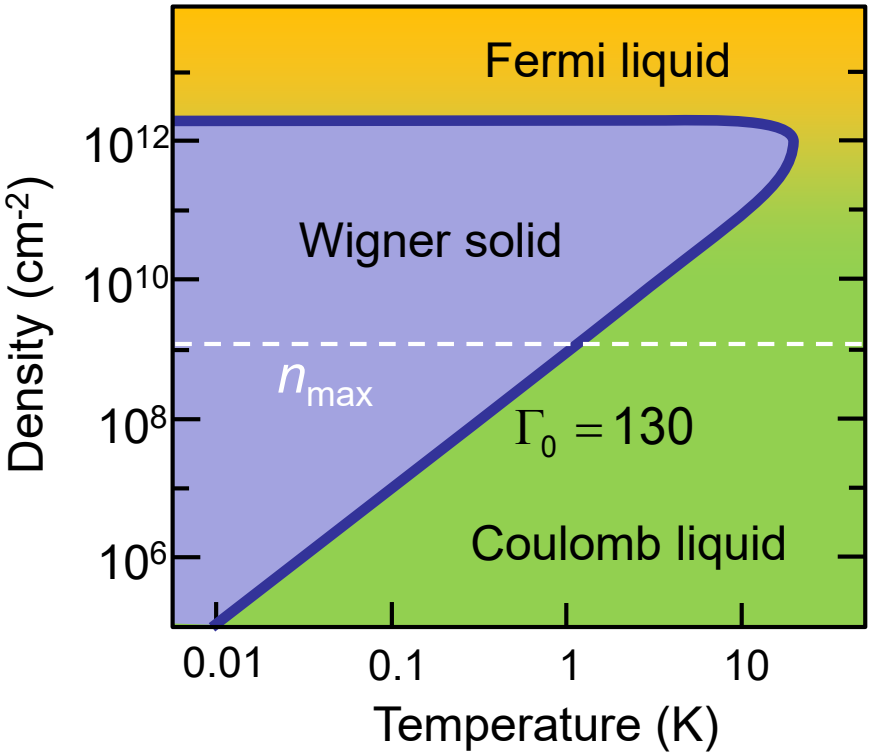
Form 2D electron systems at T<1 K



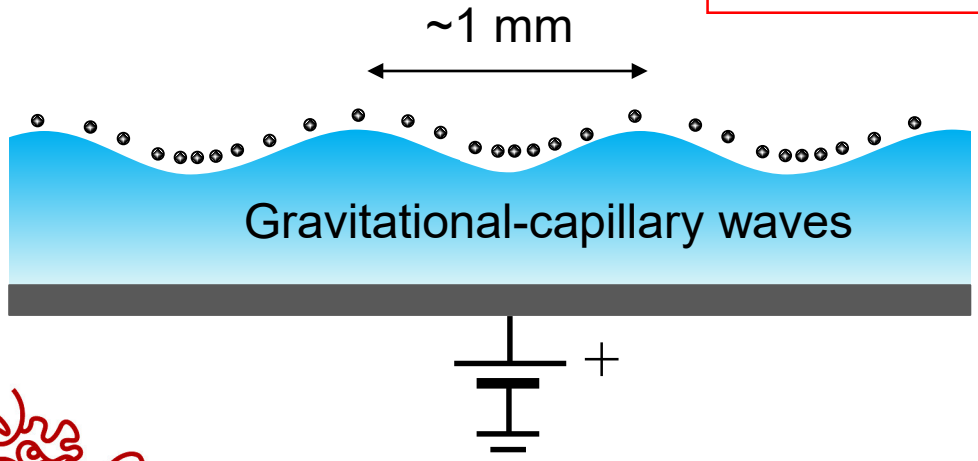
Electron Density and Phase Diagram



Brown and Grimes, 1972



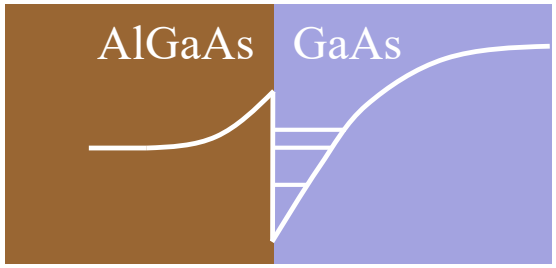
$$n_{max} \approx 2 \times 10^9 \text{cm}^{-2}$$



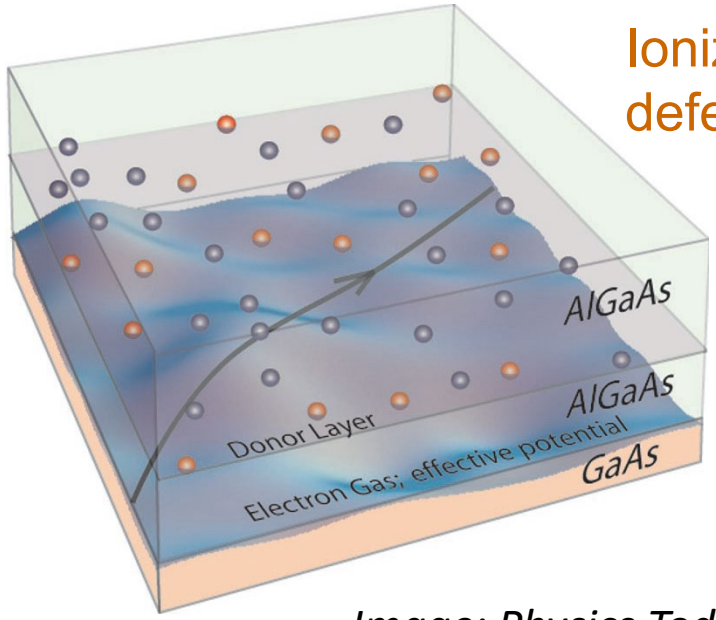
$$\Gamma = \frac{V_C}{K} = e^2 \sqrt{\pi n_s} \frac{1}{k_B T}$$

Thermal fluctuations

Scattering of electrons



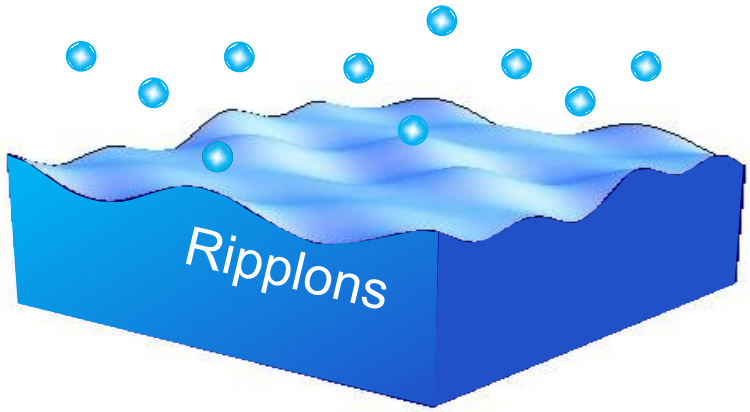
Potential landscape

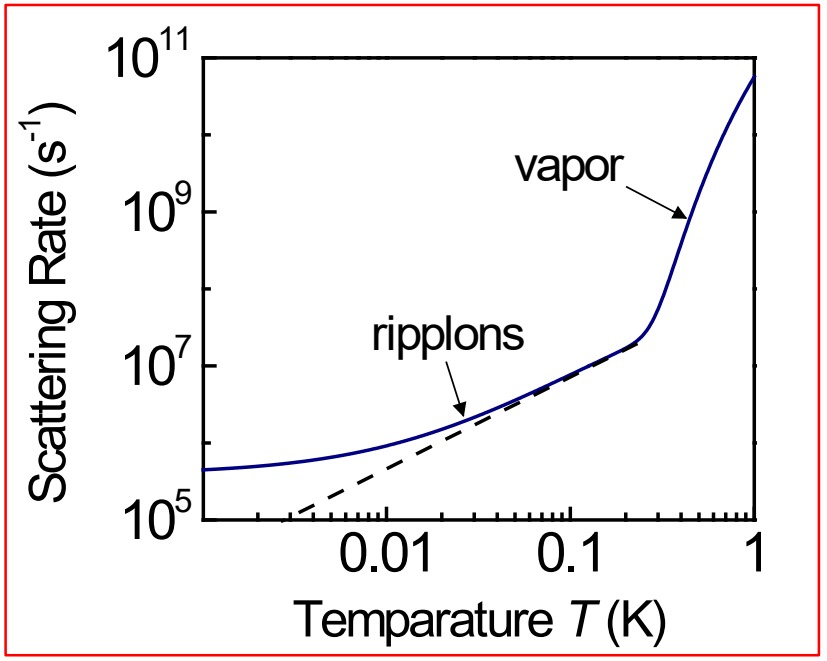


Ionized dopants, defects, etc.

*Image: Physics Today **56**, 47 (2003)*

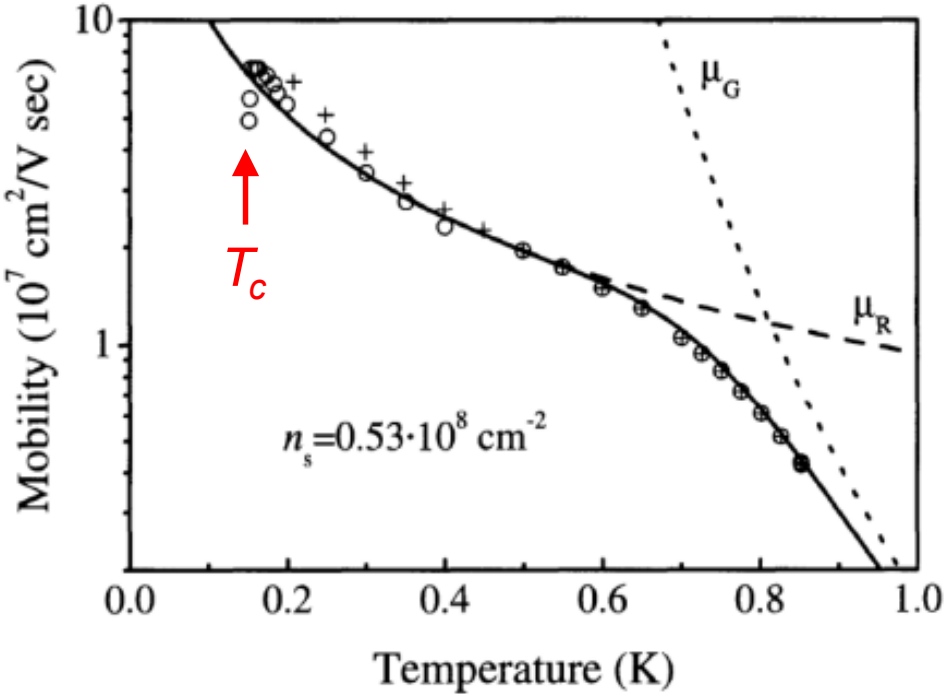
Vapor atoms



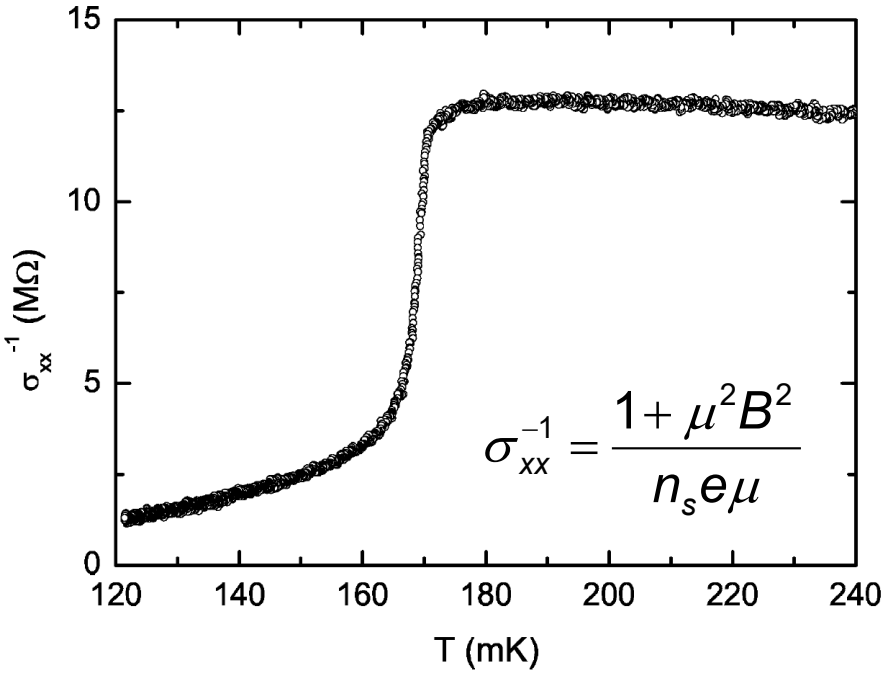


Electron Mobility

Mobility exceeding 100 M!

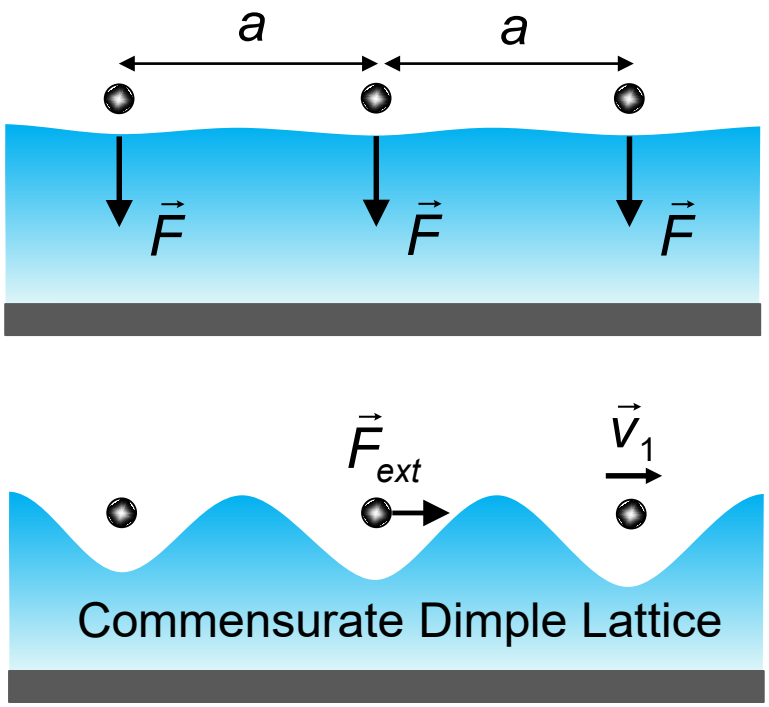


Mehrotra et al., 1984



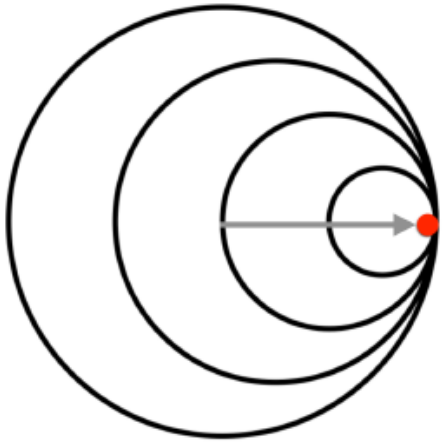
DK and Kono, 2008

Nonlinear transport of Wigner crystal (Bragg-Cherenkov scattering)

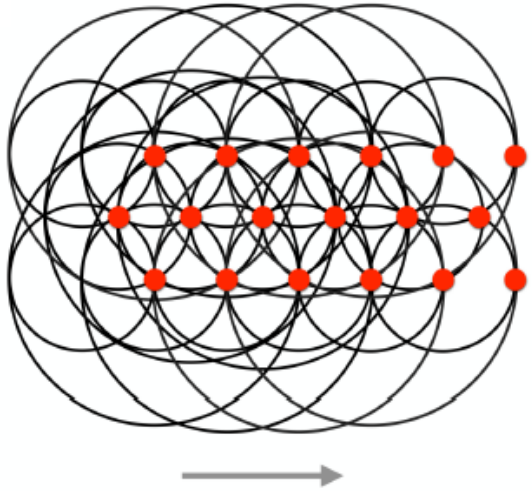


$$v_1 \equiv v_{ph}(G_1) = \sqrt{\frac{\alpha G_1}{\rho}}$$

Emission of ripplons by moving e^-:



Constructive interference of ripplons:

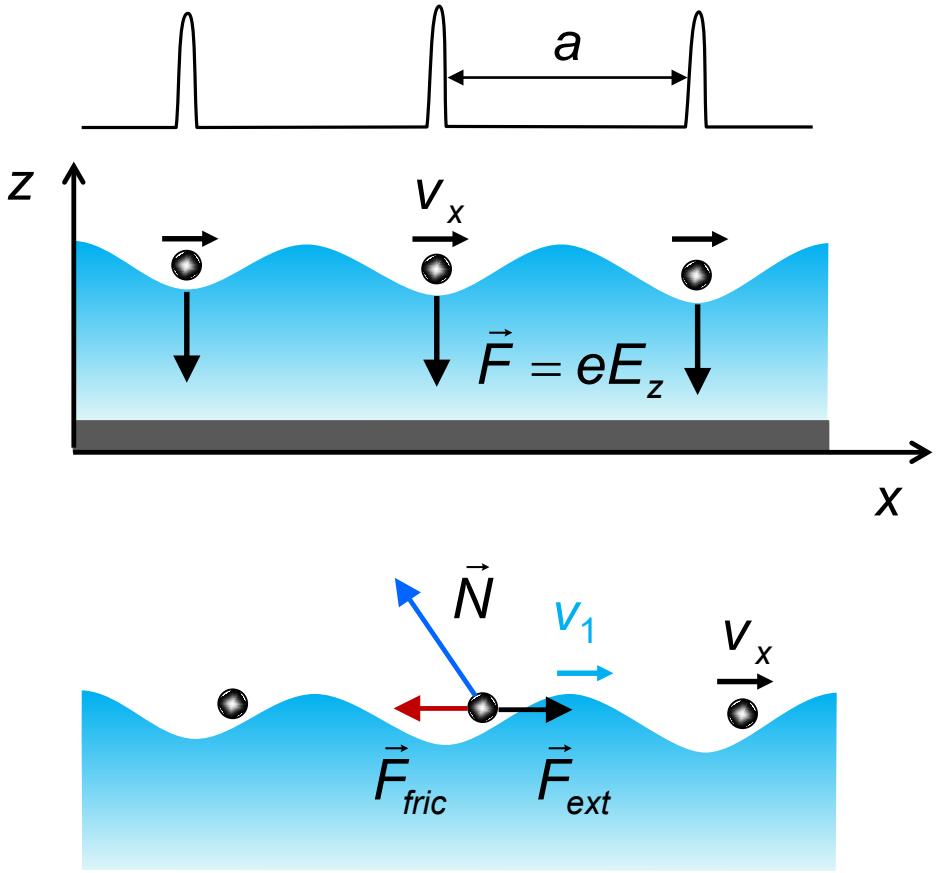


$$G_n = \frac{2\pi}{a} n$$

Bragg-Cherenkov emission of ripplons

Dykman and Rubo, 1997

Vinen, 1999



Force exerted on liquid surface:

$$F = eE_z \sum_{n=-\infty}^{+\infty} \delta(x - an - v_x t) \approx \frac{eE_z}{a} e^{i(G_1 x - G_1 v_x t)}$$

BC at liquid surface:

$$-\frac{\partial F}{\partial t} + \rho \frac{\partial^2 \phi}{\partial t^2} - \alpha \frac{\partial}{\partial z}\left(\frac{\partial^2 \phi}{\partial x^2}\right) = 0$$

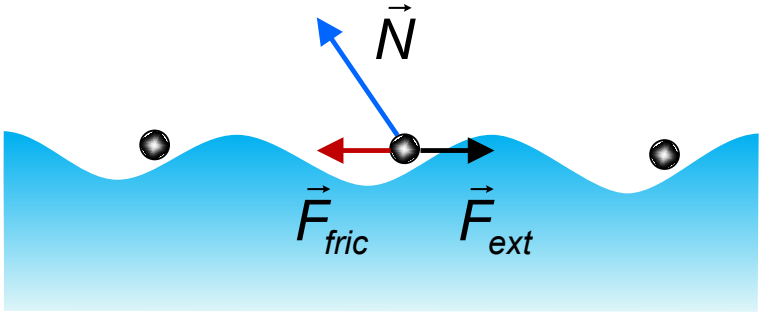
Deformation of liquid surface:

$$\varsigma(x) = \frac{eE_z}{\rho G_1}\left(\frac{1}{v_x^2 - v_1^2}\right) e^{i(G_1 x - G_1 v_x t)} \xrightarrow[v_x \to v_1]{} \infty$$

Include damping:

$$\varsigma(x) = \frac{eE_z}{\rho G_1}\left(\frac{1}{v_x^2 - v_1^2 + i v_d v_x}\right) e^{i(G_1 x - G_1 v_x t)}$$

Nonlinear transport of Wigner crystal



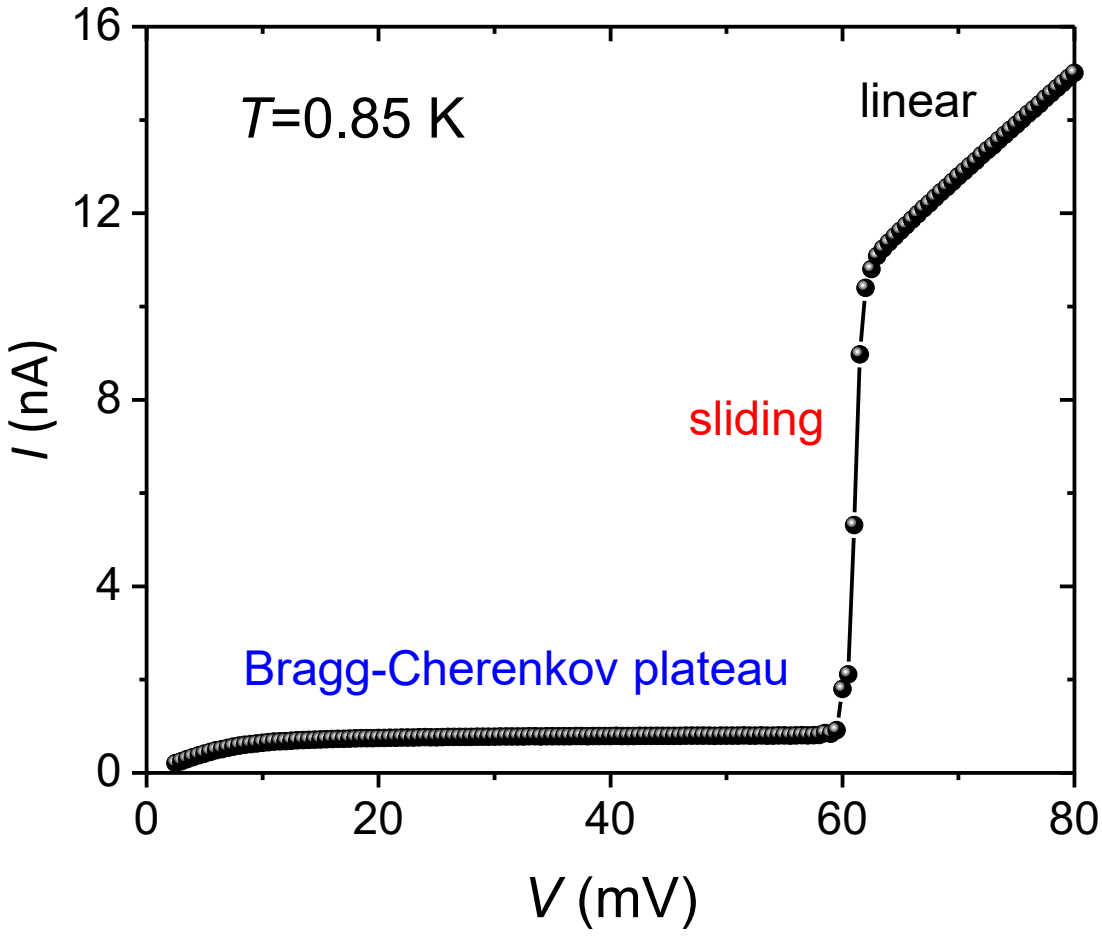
Vinen, 1999

Friction force on Wigner crystal:

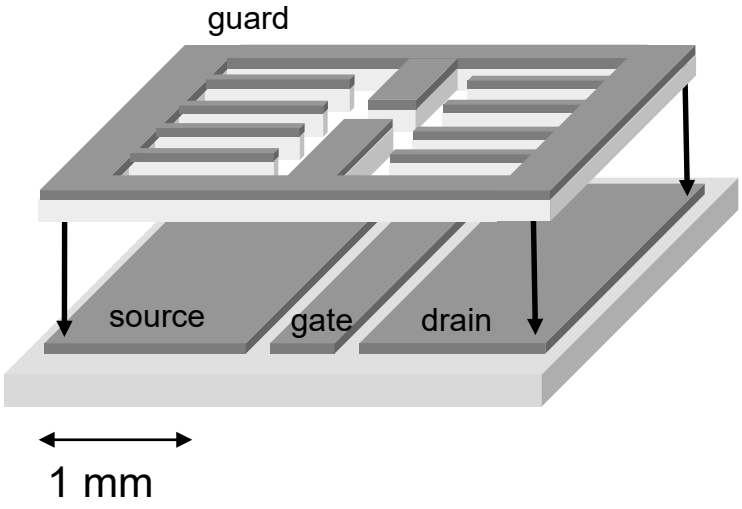
$$F_{fric} = \frac{e^2 E_z^2}{\rho a} \frac{v_d v_x}{\left(\left(v_x^2 - v_1^2\right)^2 + v_d^2 v_x^2\right)}$$

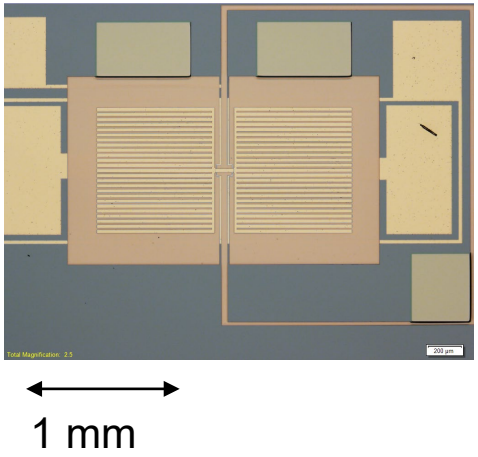
$$F_{fric}^{(\max)} = \frac{e^2 E_z^2}{\rho a v_d v_1} < F_{ext}$$

I-V curve

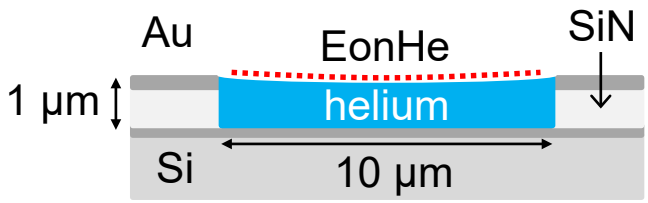


Microchannel devices

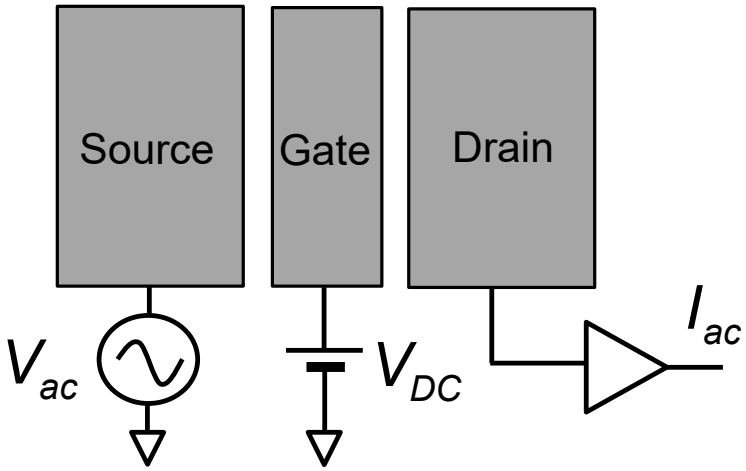


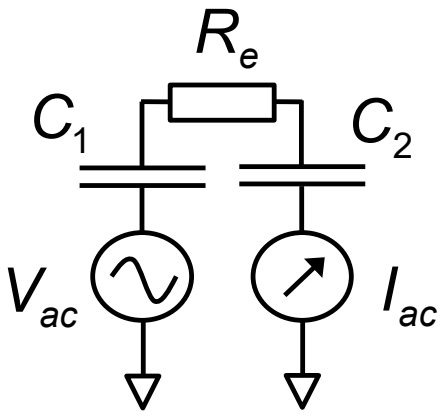


Central Channel

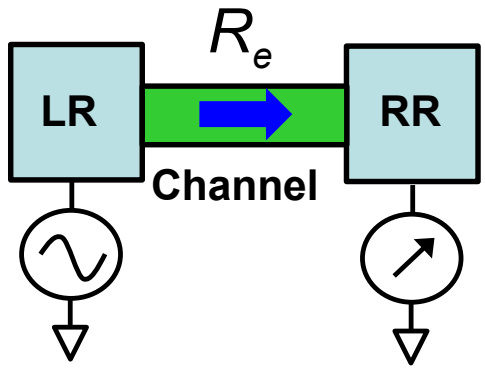


Helium FET



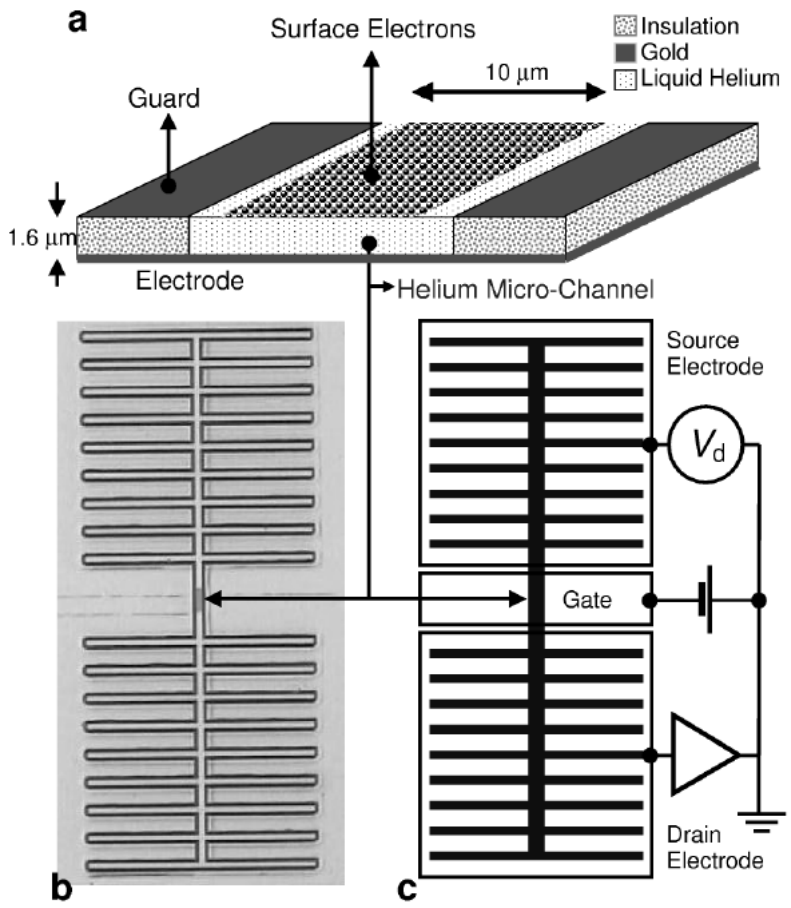


Sommer-Tanner



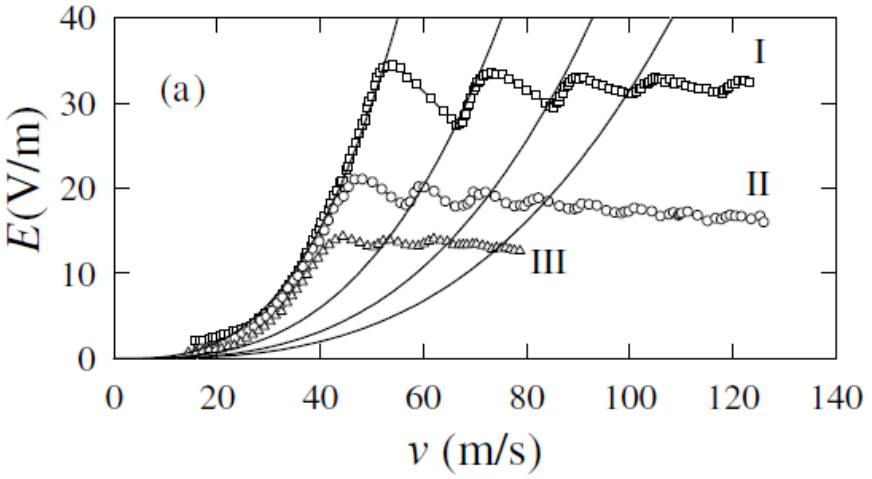
2-terminal device

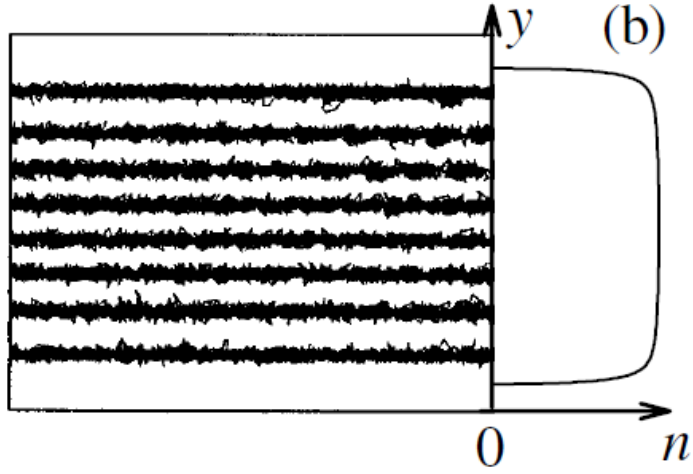
The first microchannel device



Glasson et al., PRL 2001

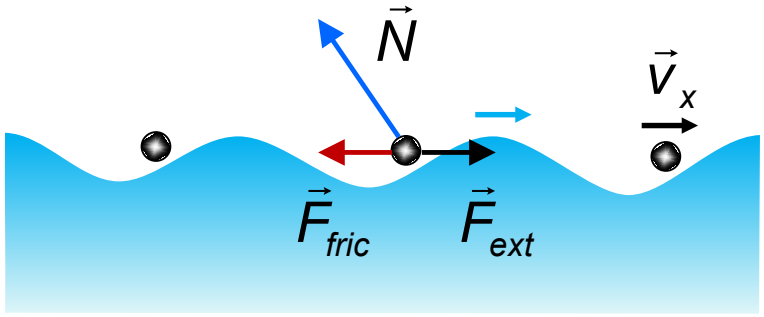
Force-velocity (field-current) curve





Stripe phase of Wigner crystal

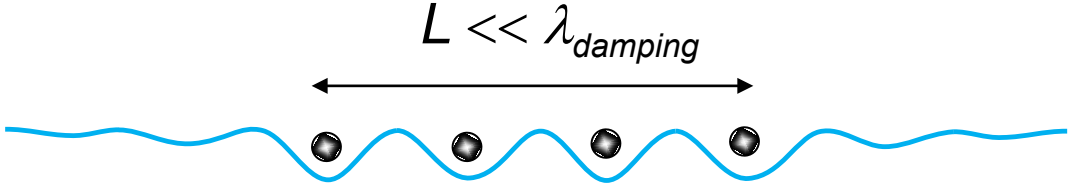
Damping in Vinen's model



Vinen, 1999

Damping parameter v_d

- Damping of ripplons due to dissipation
- Finite size of Wigner crystal



Friction force on Wigner crystal:

$$F_{fric} = \frac{e^2 E_z^2}{\rho a} \frac{v_d v_x}{\left(\left(v_x^2 - v_1^2\right)^2 + v_d^2 v_x^2\right)}$$

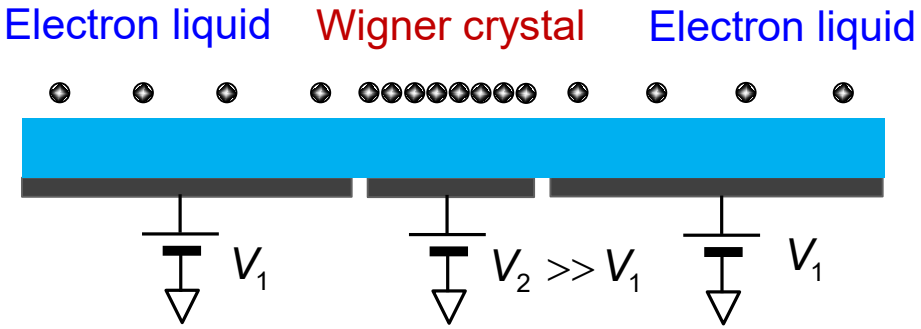
$$F_{fric}^{(\max)} = \frac{n_s e^2 E_z^2}{\rho v_d v_1}$$

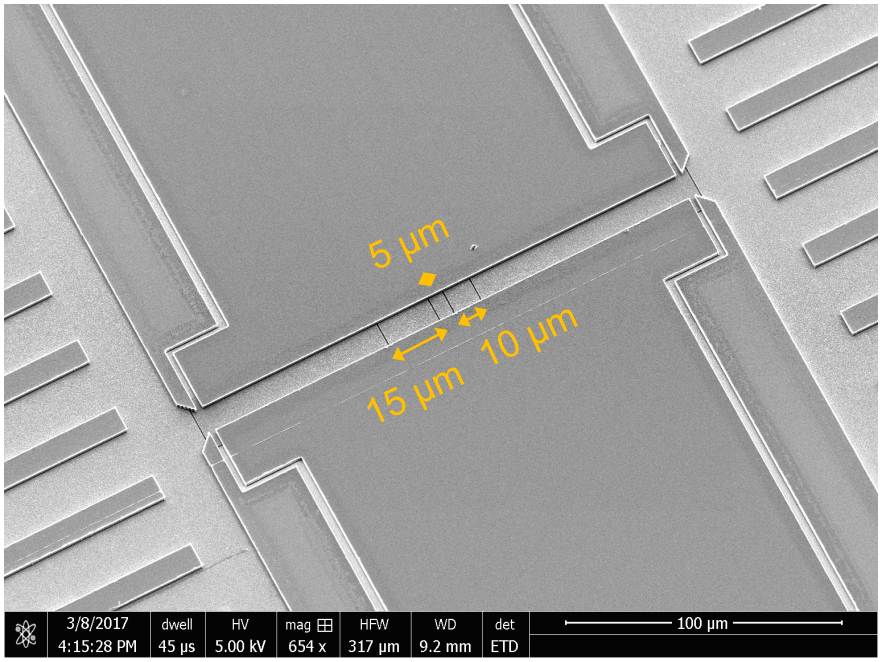
$$F = eE_z \sum_{n=0}^{+N} \delta(x - an - v_x t) \approx$$

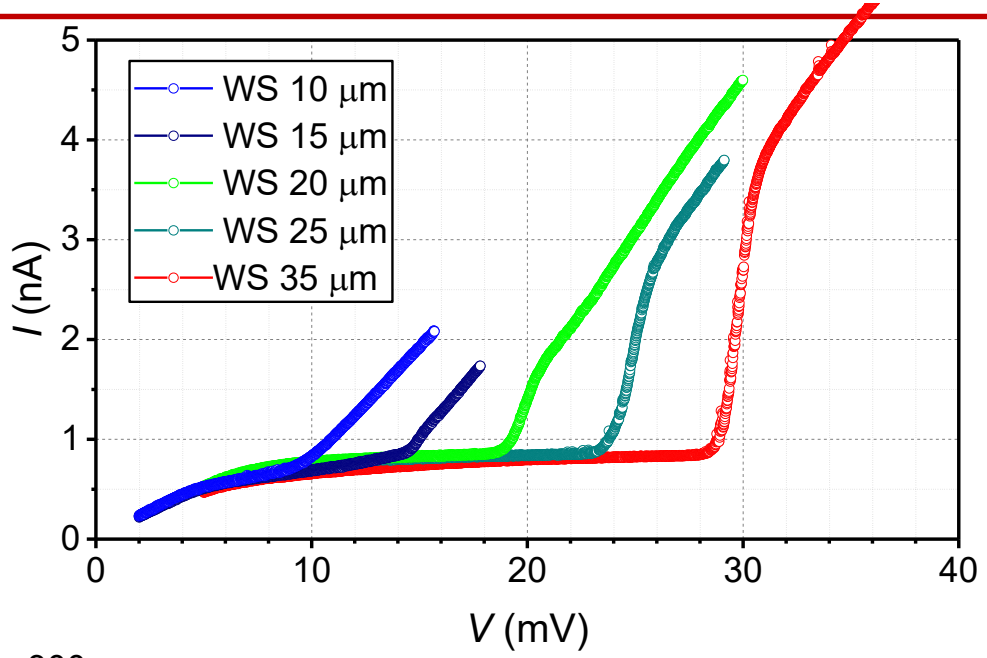
$$\approx \frac{NeE_z}{\pi} \sum_{m=-\infty}^{+\infty} e^{i(qx - mqv_x t)} \frac{\sin\left[L(q - mG_1)/2\right]}{L(q - mG_1)}$$

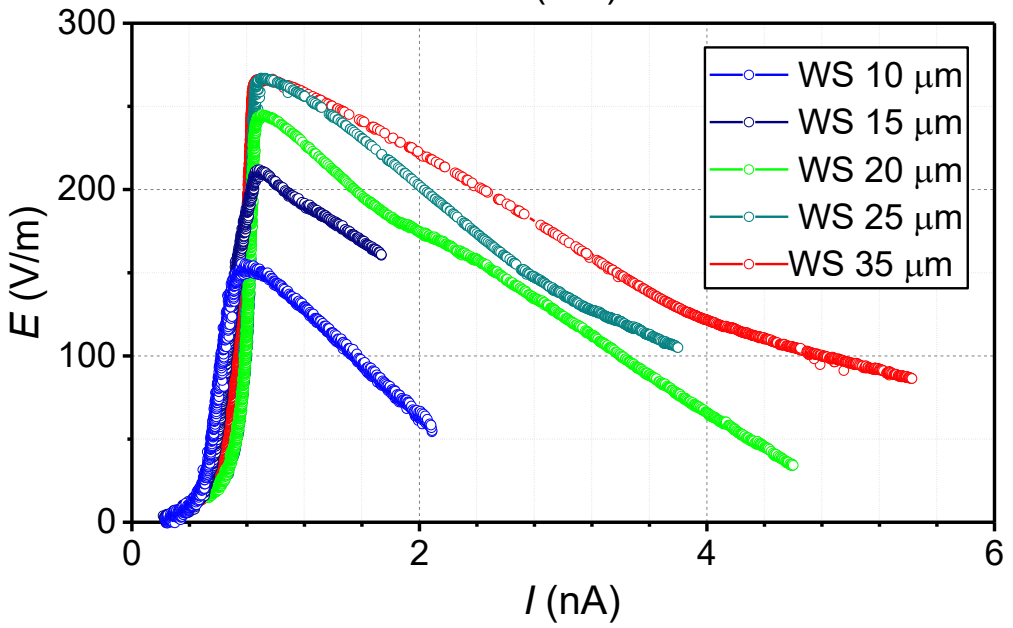
$$F_{fric}^{(\max)} = \frac{n_s e^2 E_z^2}{\rho v_d v_1} \left(1 - e^{-\frac{LG_1}{2}\left(\frac{v_d}{v_1}\right)}\right)$$

Wigner crystal of finite size



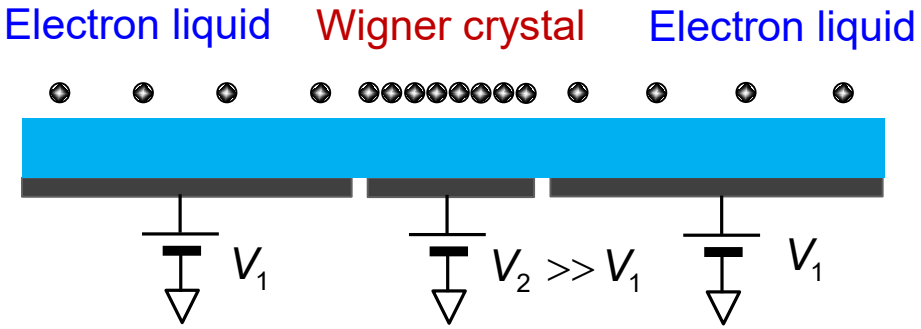


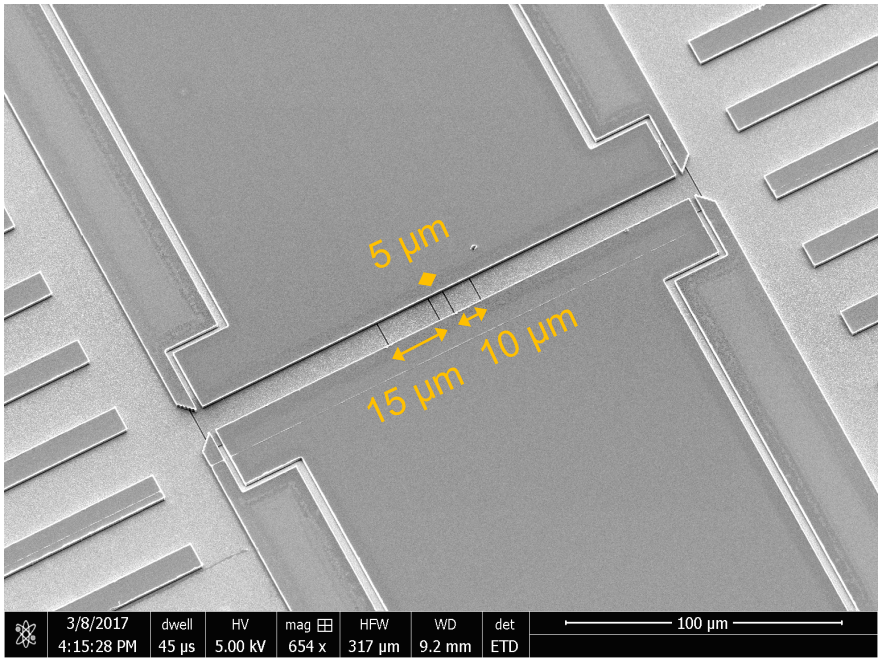




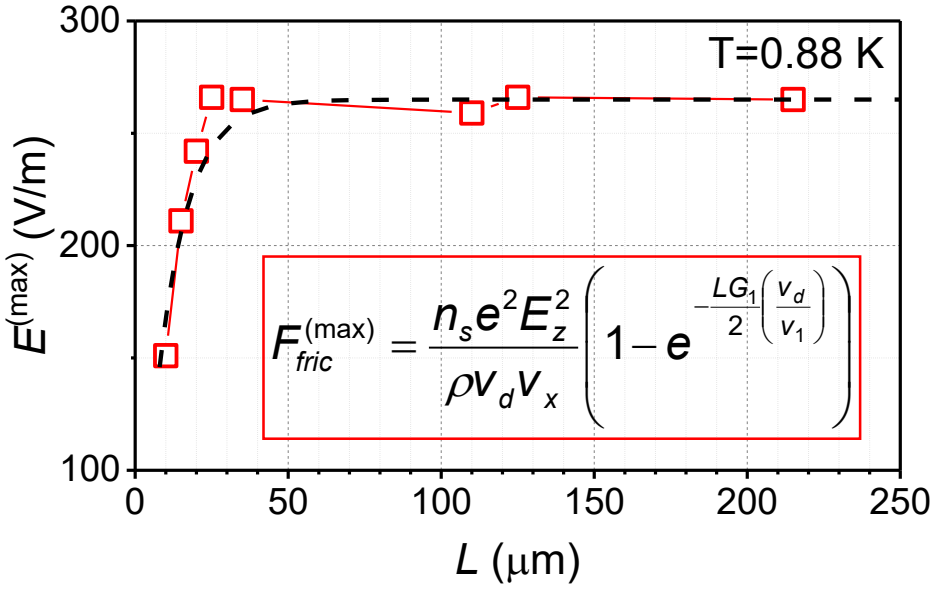
*Lin et al., PRB **98**, 085412 (2018)*

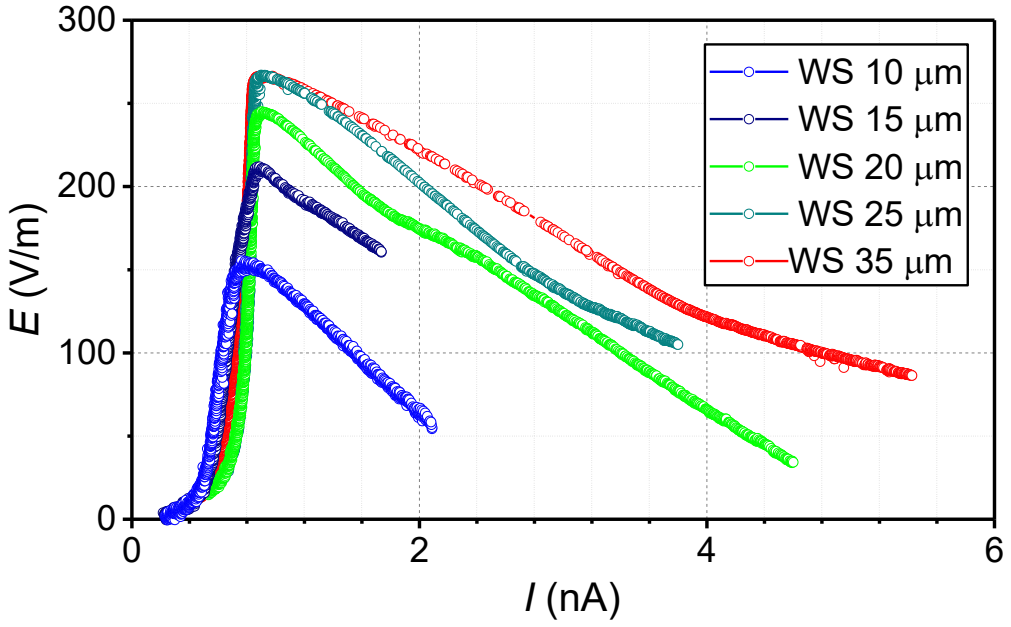
Wigner crystal of finite size



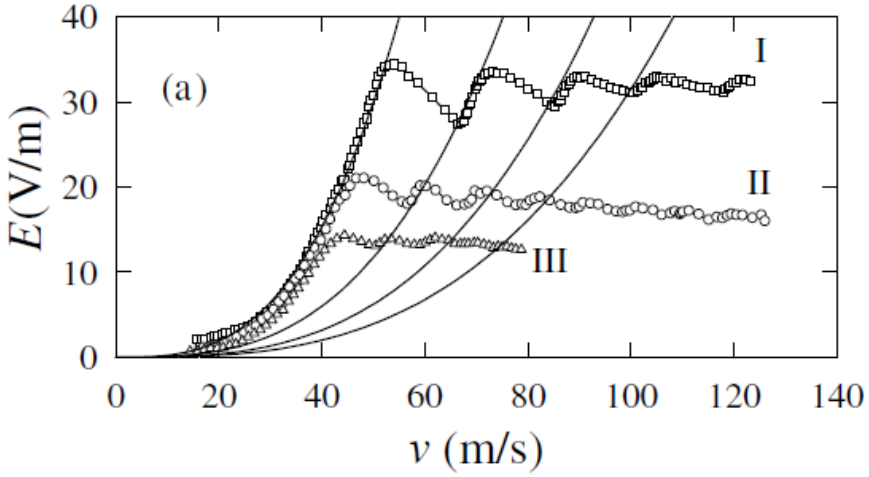


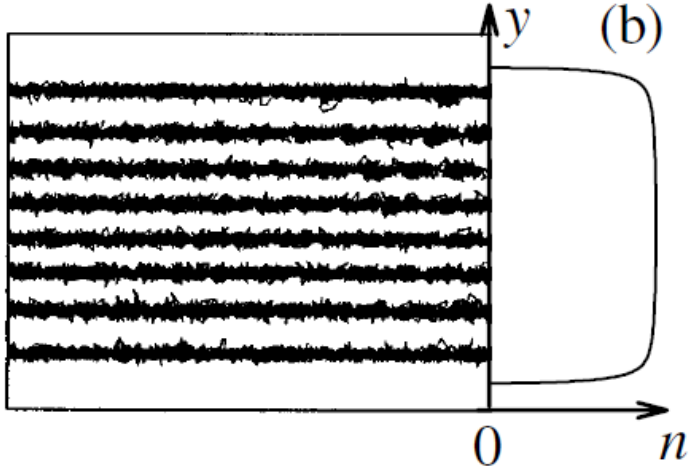
*Lin et al., PRB **98**, 085412 (2018)*



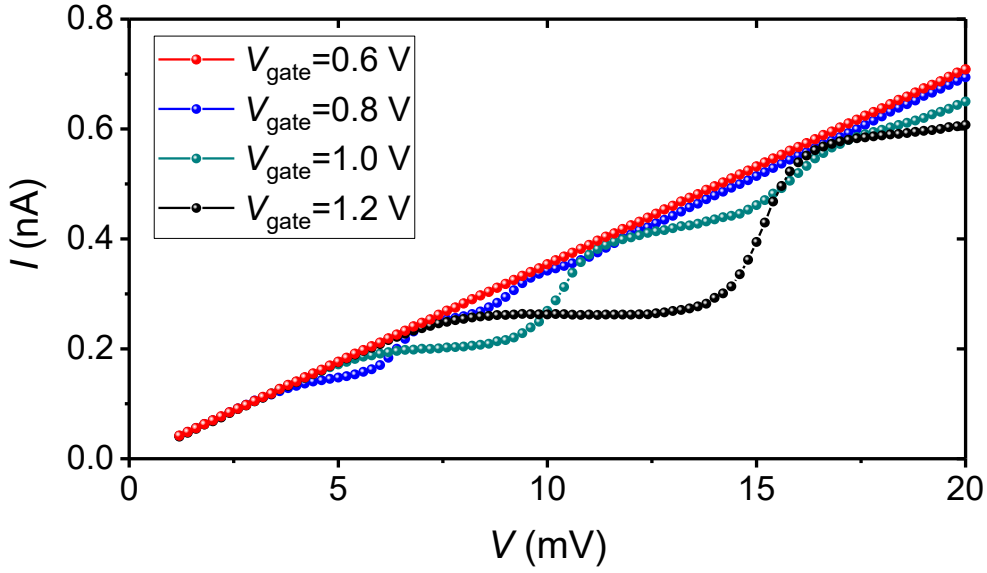


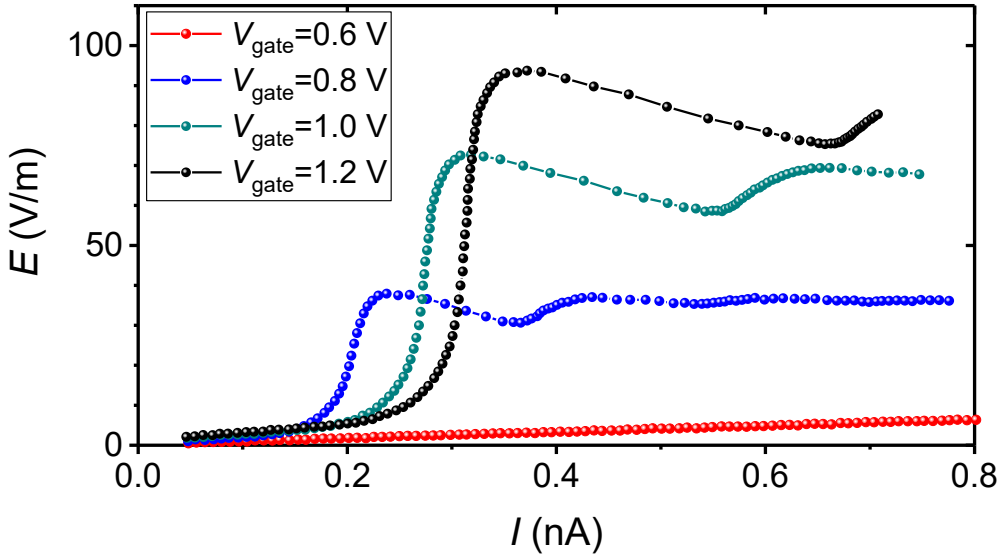
Stripe phase Wigner crystal





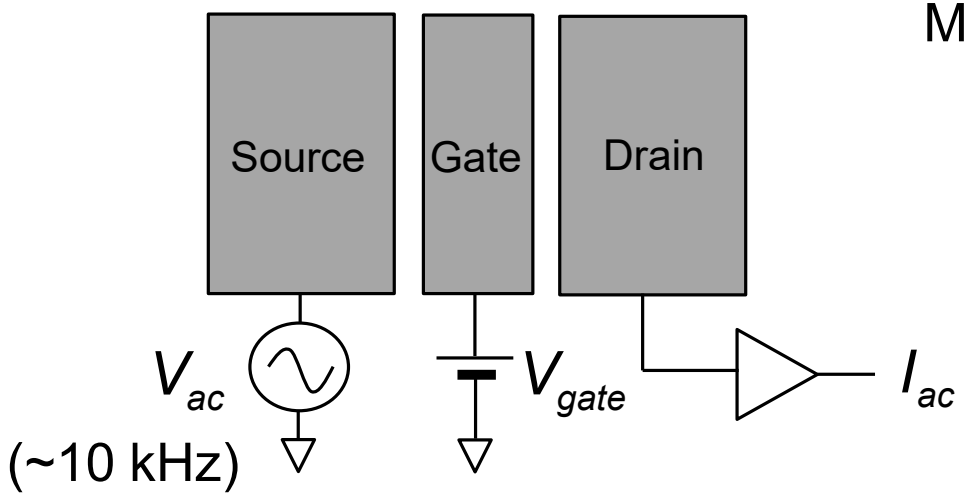
Glasson et al., PRL 2001





Time-resolved measurements

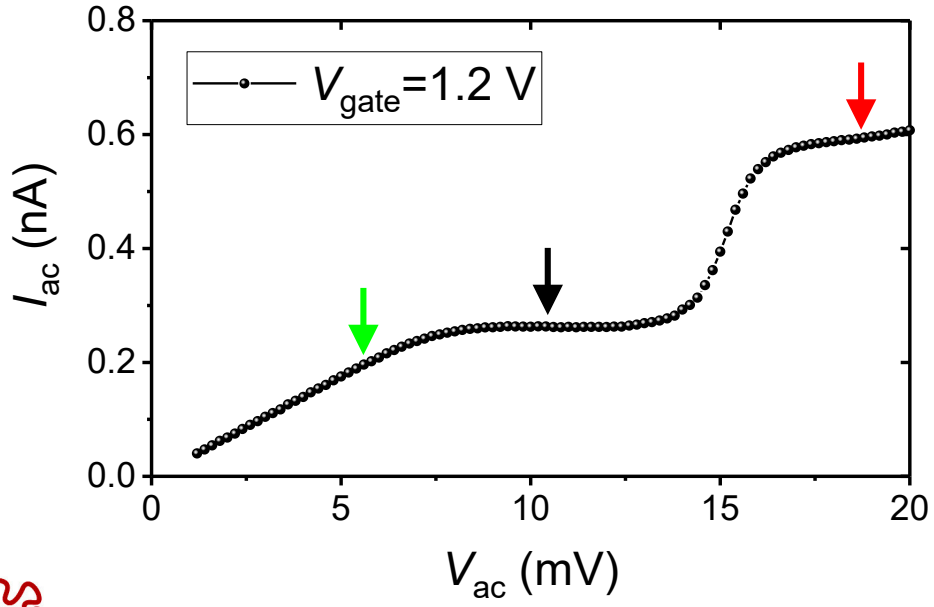
Helium FET



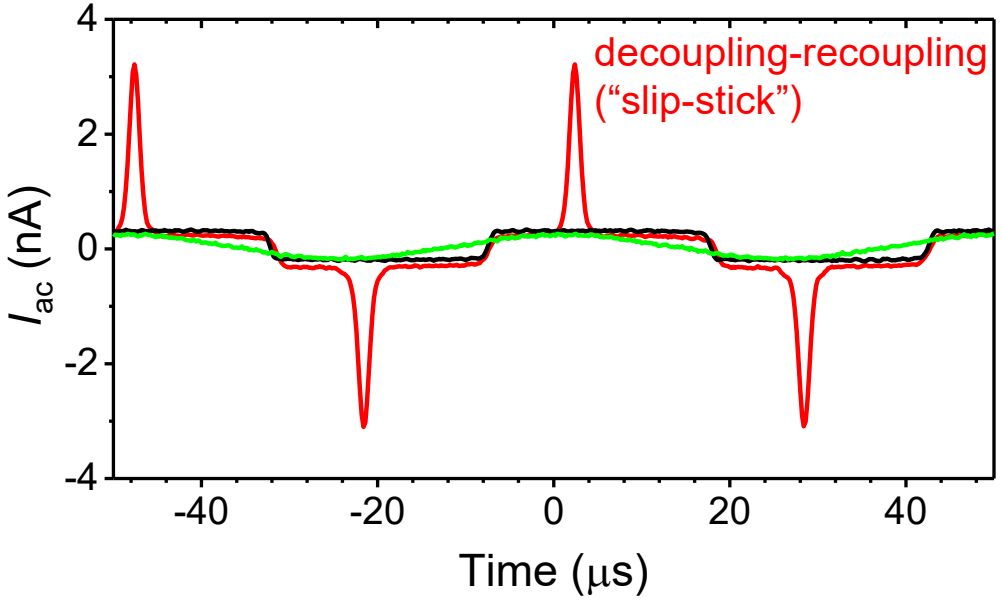
Measured current I_{ac}

- Time-averaged using locking-in
- Time-resolved using fast oscilloscope

Rees et al., PRL 2016

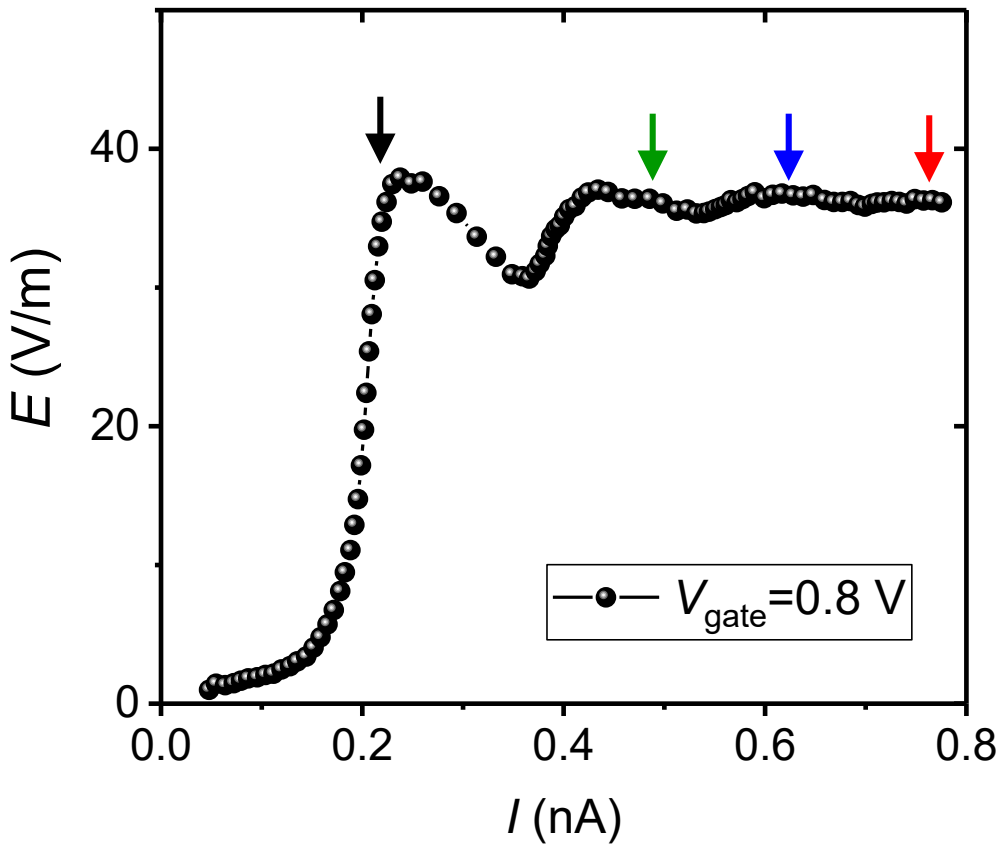


Time-resolved response

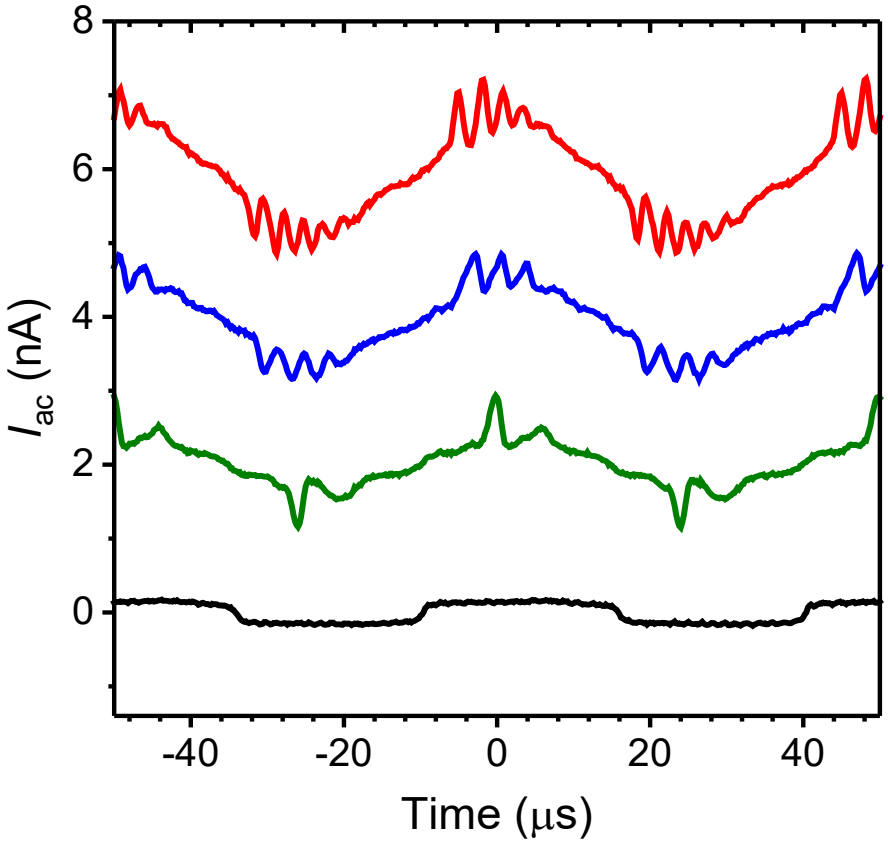


Repetitive Slip-Stick Transitions

Time-averaged response

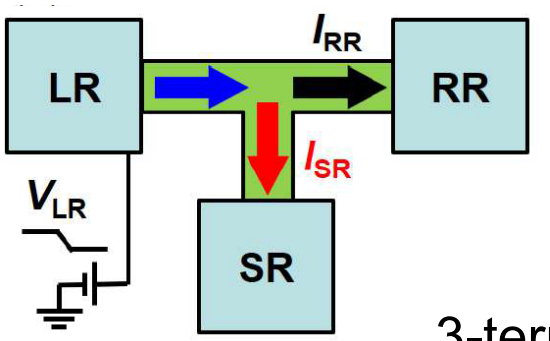


Time-resolved response

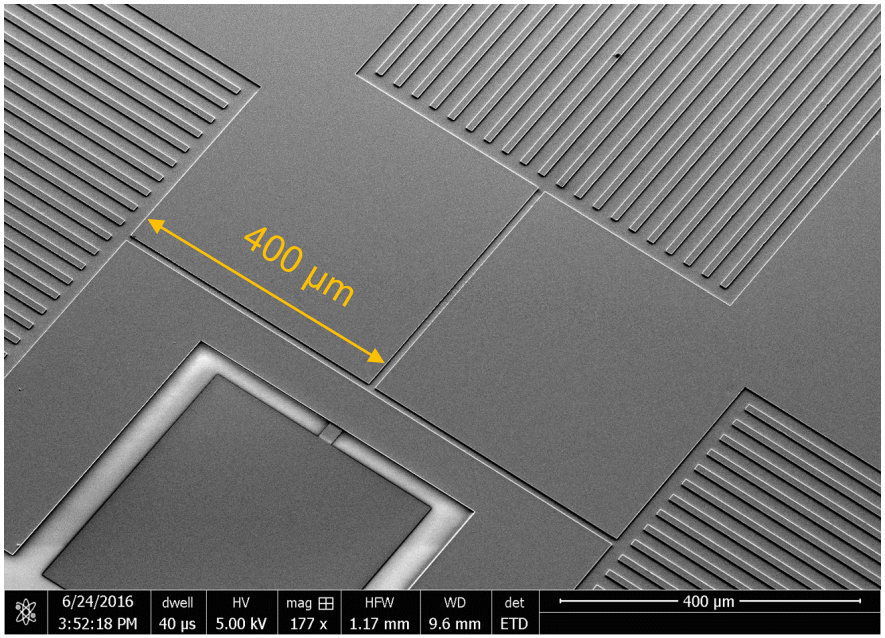


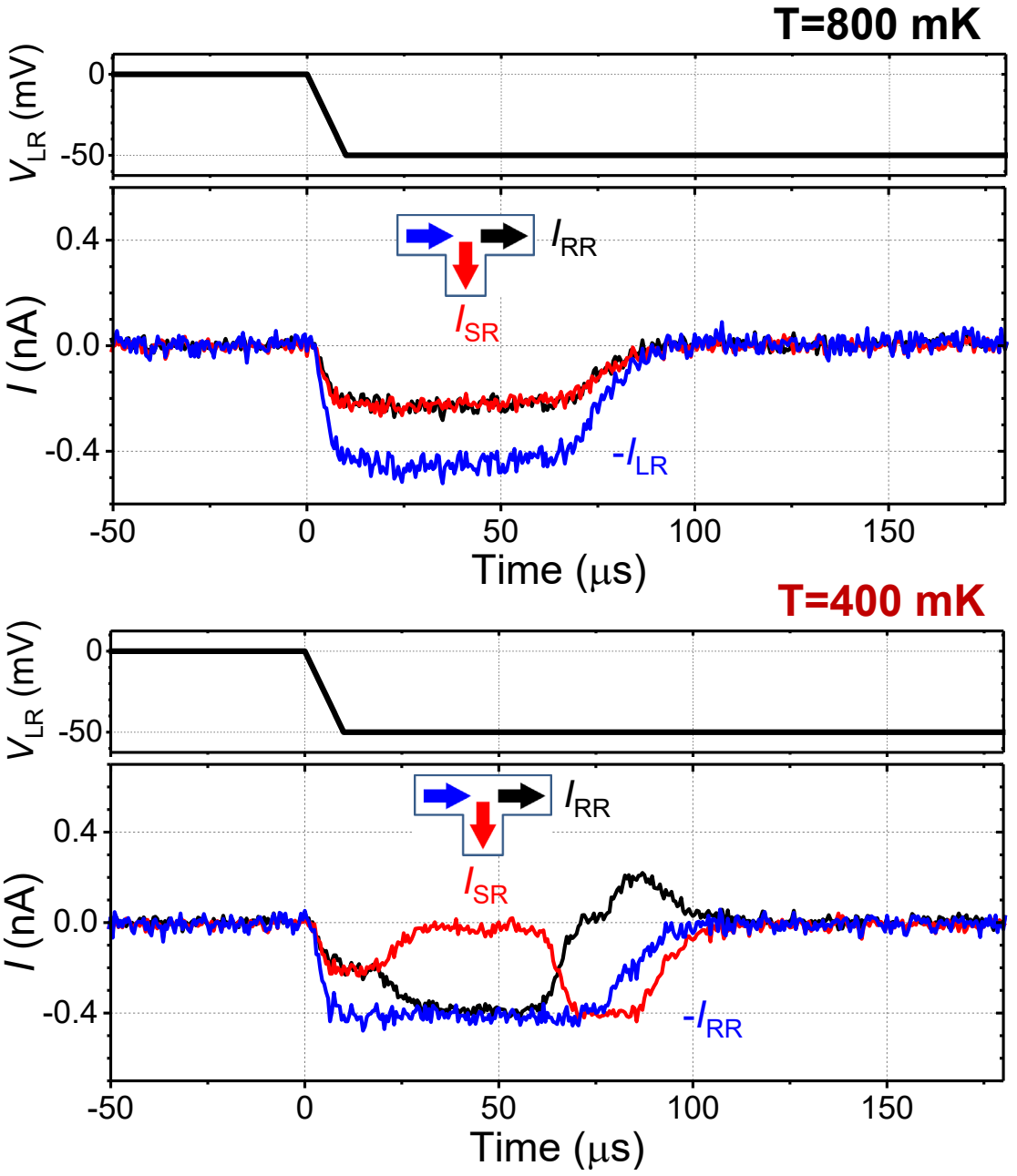
*Zou et al., **PRB** 104, 045427 (2021)*

Transport through 3-terminal device



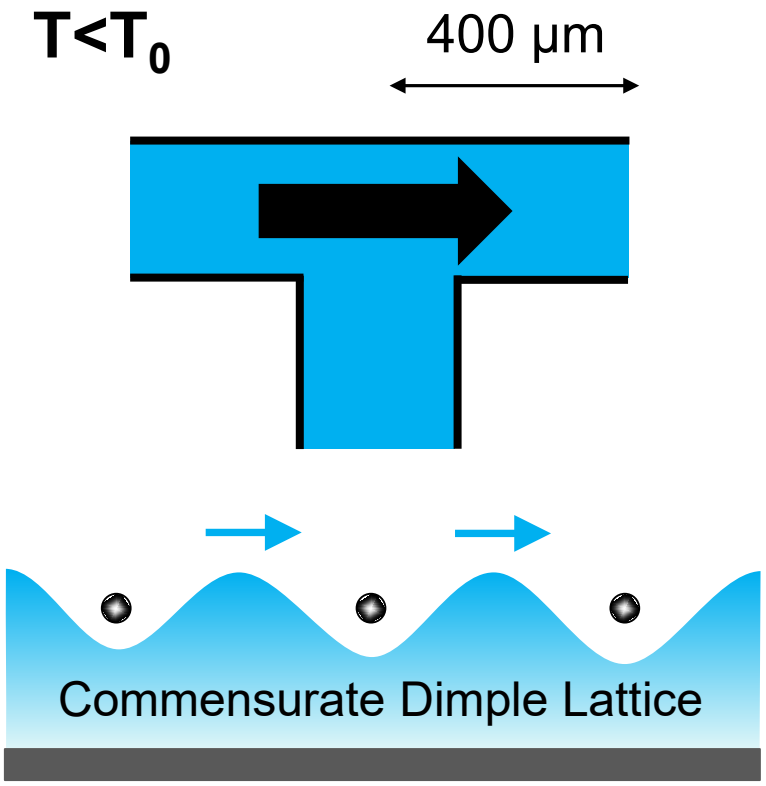
3-terminal device

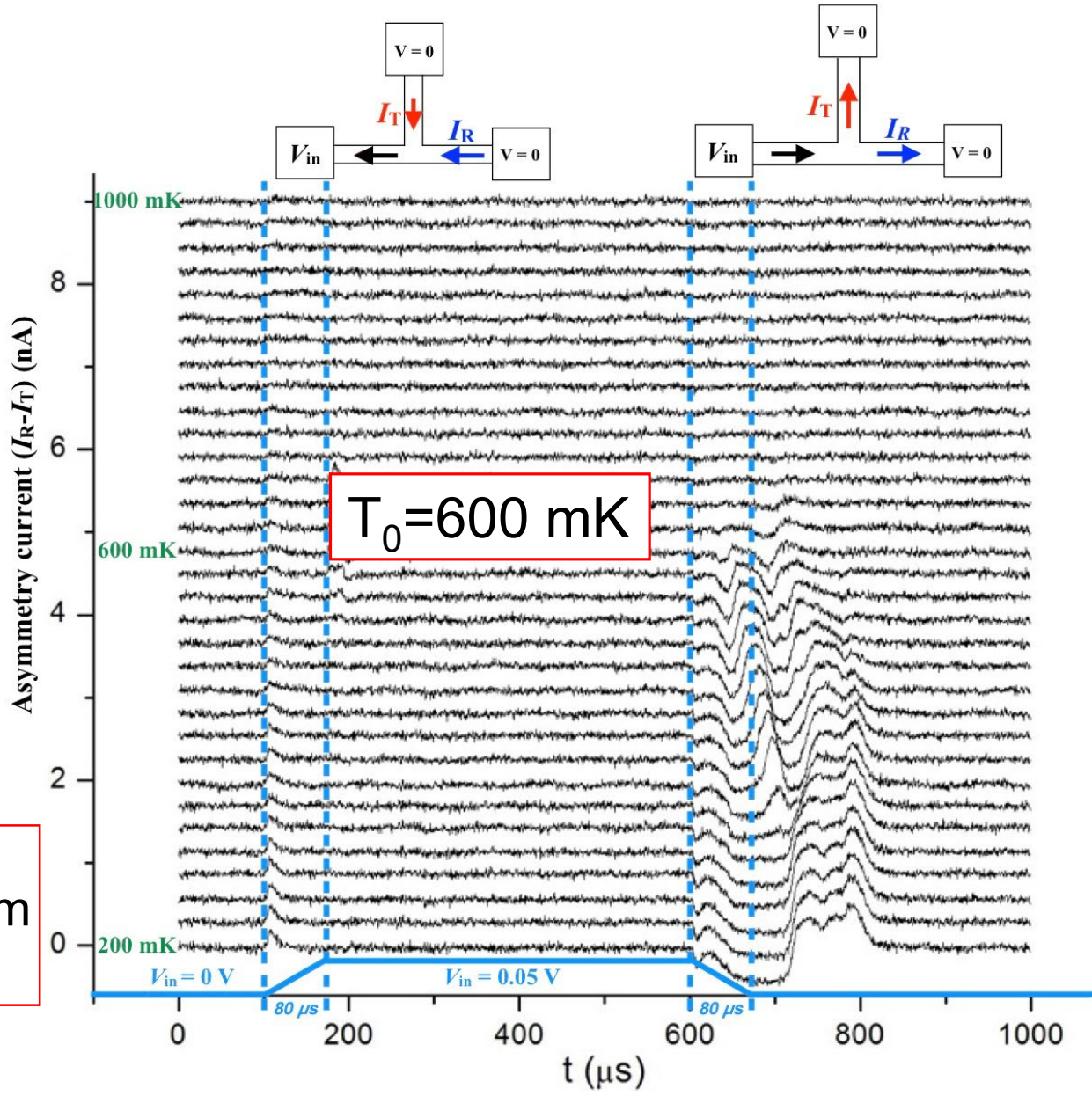




*Badrutdinov et al., PRL **124**, 126803 (2020)*

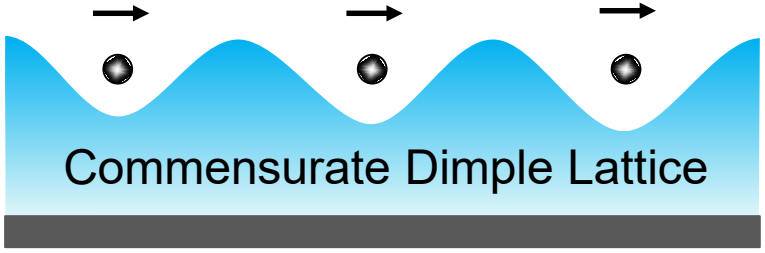
Unidirectional (polaronic) transport

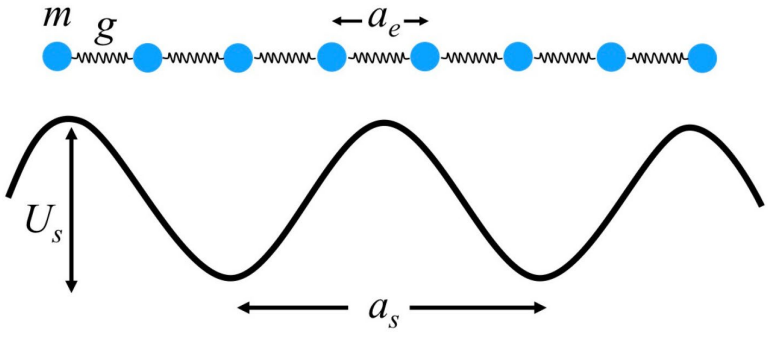




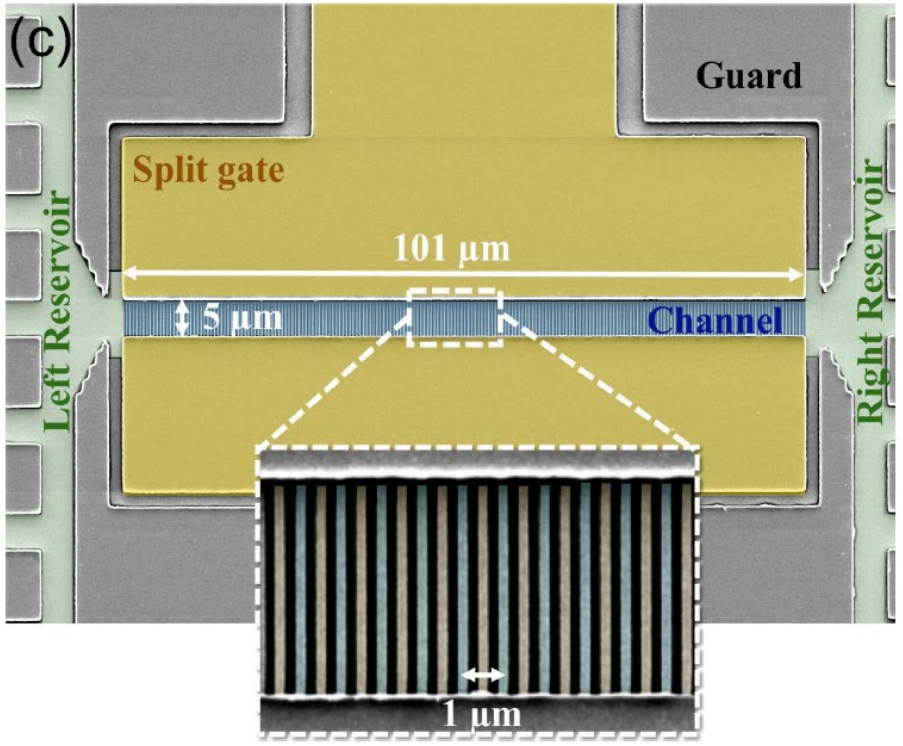
$$\lambda_{damping} = \frac{\pi^2 \hbar G_1^2}{90 \rho \omega_{G_1}} \left(\frac{k_B T}{\hbar s} \right)^4 \Bigg|_{600\,\mathrm{mK}} = 230\ \mu\mathrm{m}$$

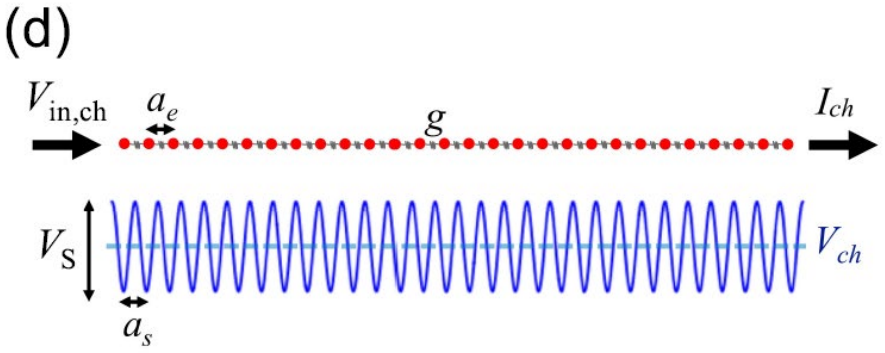
Prospects





Frenkel-Kontorova Model (FKM)





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