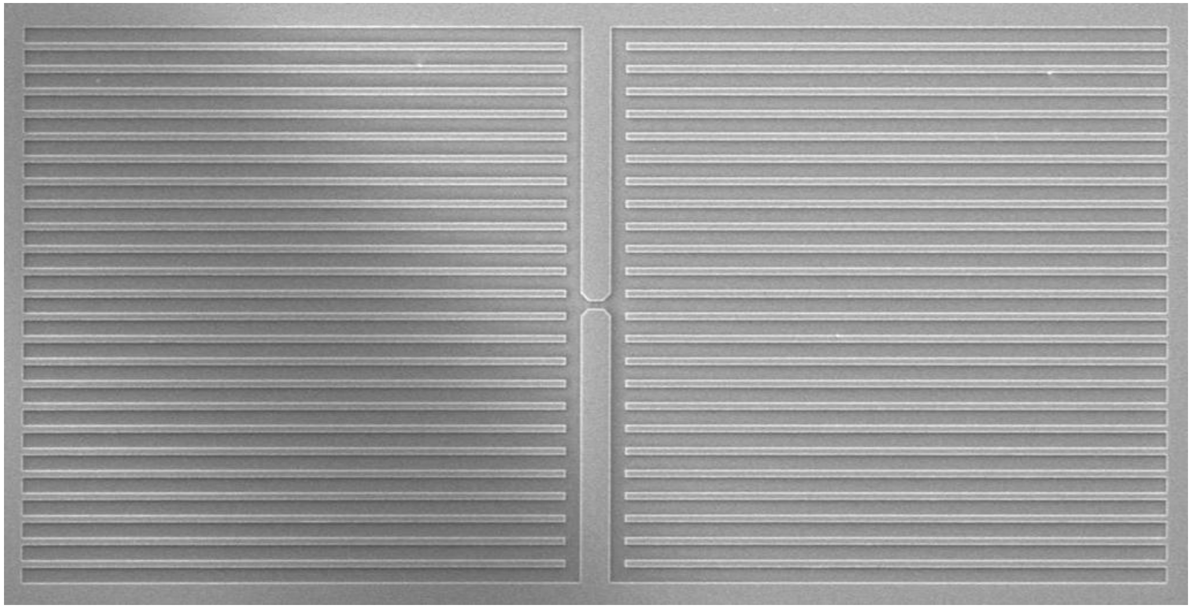
Transport Measurements of Electrons on Helium at a Point Constriction



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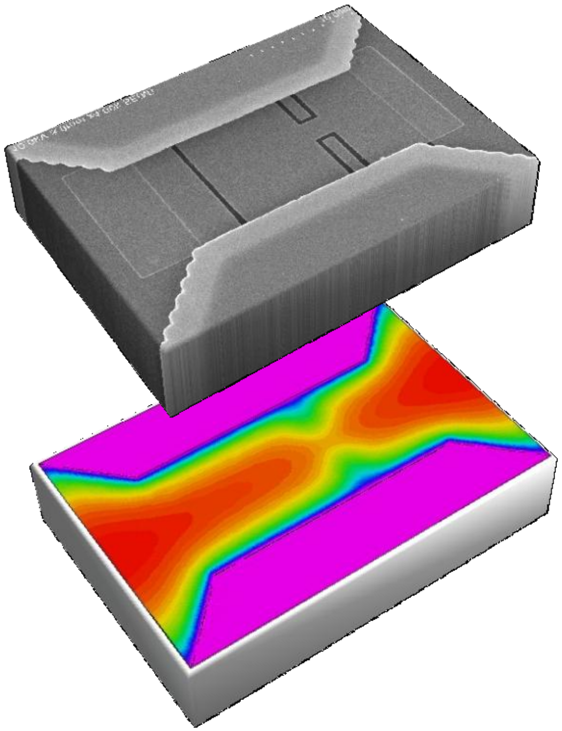
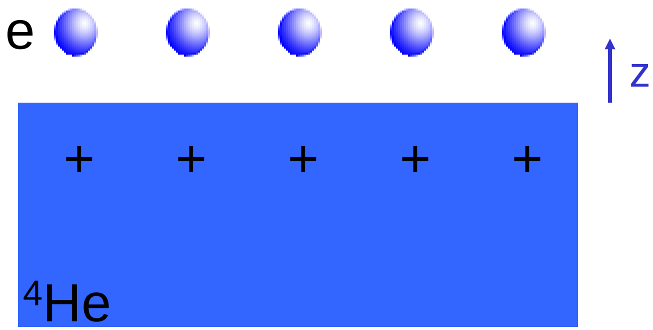
RIKEN: Isao Kuroda and Kimitoshi Kono
Konstanz: Moritz Hofer and Paul Leiderer

Outline

- Introduction – Mesoscopics with Electrons on Helium
- Motivation - Possible new directions
- A microchannel point-contact device
- Results
- Conclusions



Electrons on Helium



Electrons bound to a liquid Helium surface:

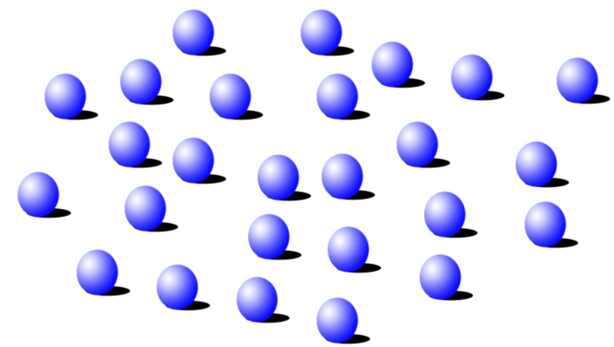
$V(z) = -Qe^2/4\pi\varepsilon_0 z$ $Q = (\varepsilon-1) / 4(\varepsilon+1)$

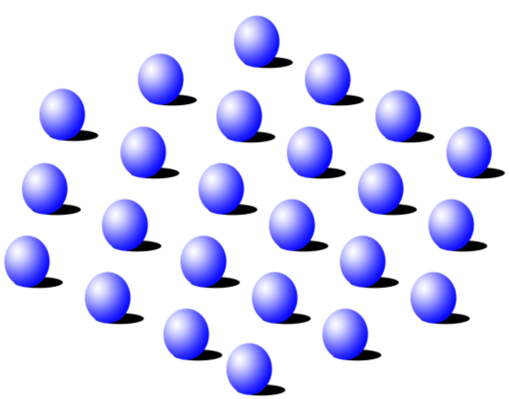
1 eV barrier at liquid surface: At 1 K z_0 = 11 nm

A (nearly) ideal 2D electron system, $n_s \sim 10^7 - 10^9$ cm^{-2}

Strong Coulomb interaction: Interelectron distance $d_{e\text{-}e} \sim 1$ μm

A non-degenerate, classical 2D liquid



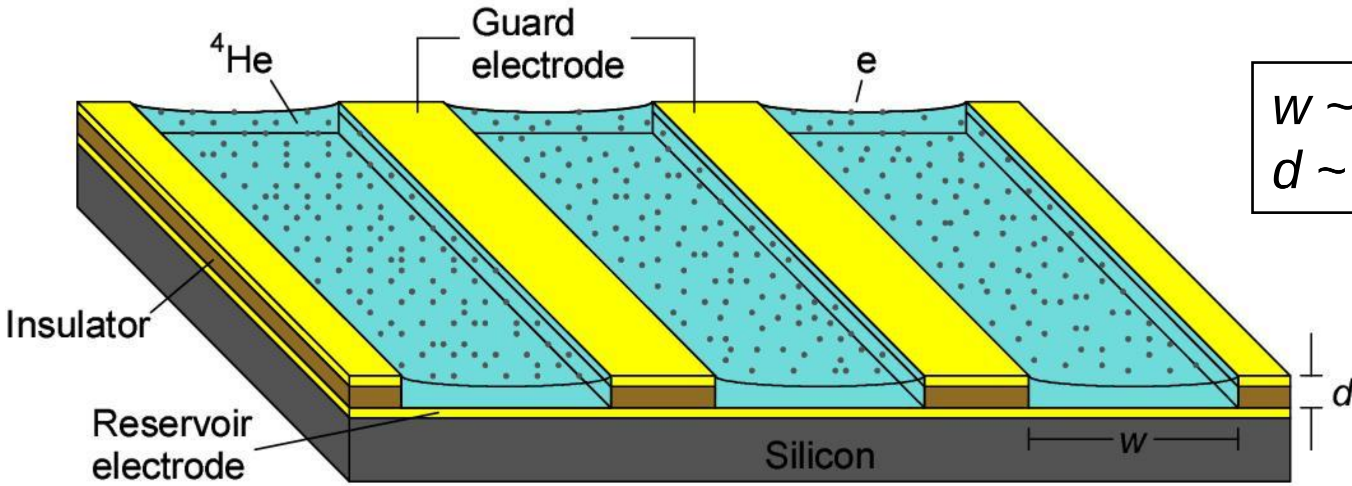


At low temperatures (< ~1 K), we expect the Wigner crystal to form:

$$\Gamma = \frac{e^2\sqrt{(\pi n_e)}}{4\pi\varepsilon\varepsilon_0 k_B T} \qquad (E_{coulomb} / E_{thermal})$$

Wigner crystal for Γ ≥ 127

Microchannels filled by capillary action can be used to perform experiments on small numbers of surface-state electrons:



$w \sim 20\ \mu m$
$d \sim 1\ \mu m$

For a microchannel a distance *h* above bulk superfluid we have a curved surface:

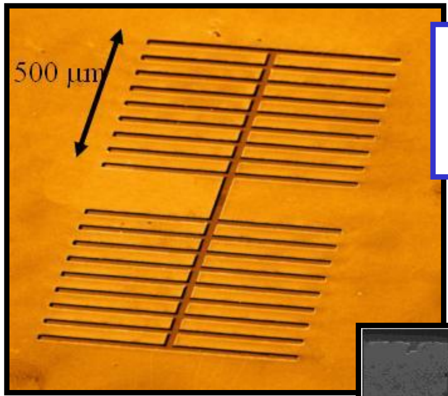
$$R = \alpha/\rho g h + n_s^2 e^2/2\varepsilon\varepsilon_0$$

α = surface tension coefficient, ρ = density

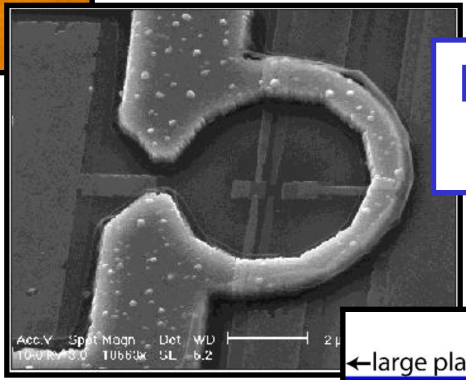
→ For typical dimensions and densities, the change in height at the channel centre:

<u>Δd ~ 100 nm</u>

Experiments with microfabricated devices

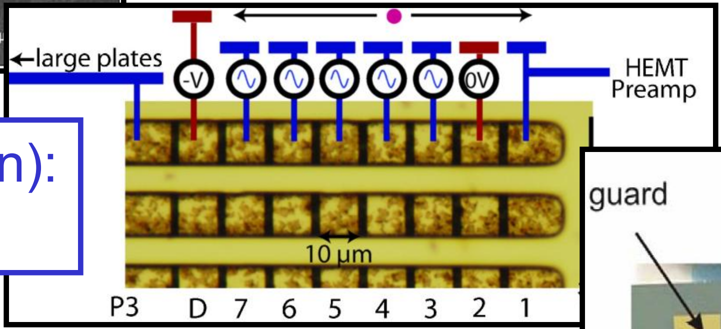


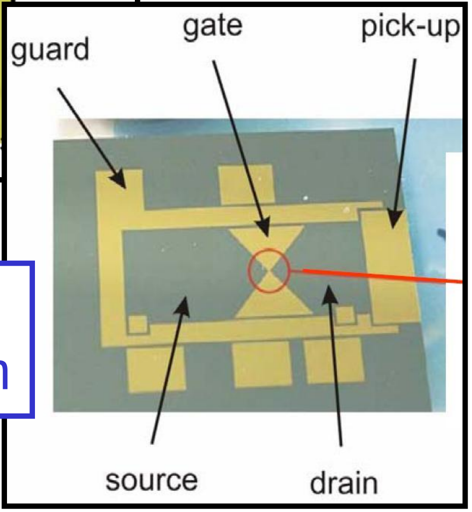
Microchannels (Eindhoven, Royal Holloway, RIKEN):
Wigner solid transport in confined geometries



Electron traps (Royal Holloway, Saclay):
SET detection of single electrons

‘Clocking’ in channels (Princeton):
Ultra-efficient charge transfer





Helium Field Effect Transistor (Konstanz):
Split-gate constriction for electrons on a helium film

And Yale cavity QED… etc

We can improve:

- Experimental control (we need to capture electrons!)
- Measurement sensitivity (new read-out devices?)
- Understanding (potential profile, electric field, mobility…)
- Sample Dimensions (distance between electrons is ~ 1 μm)

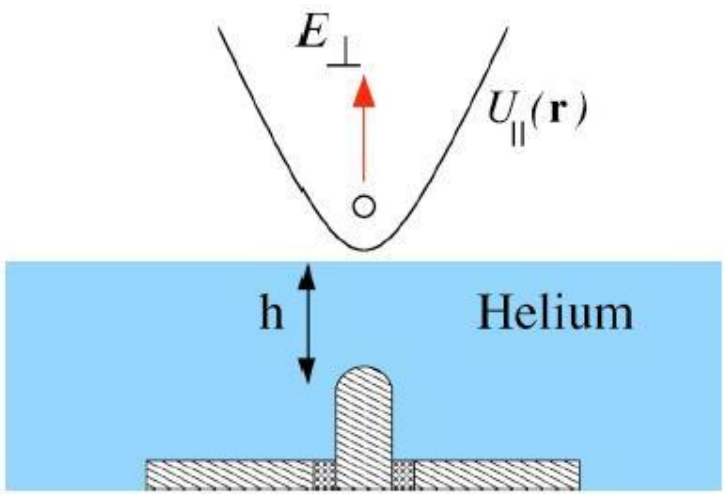
If so, a variety of new experiments may be possible…

SCIENCE VOL 284 18 JUNE 1999

Quantum Computing with Electrons Floating on Liquid Helium

P. M. Platzman[1]* and M. I. Dykman[2]

A quasi–two-dimensional set of electrons ($1 < N < 10^9$) in vacuum, trapped in one-dimensional hydrogenic levels above a micrometer-thick film of liquid helium, is proposed as an easily manipulated strongly interacting set of quantum bits. Individual electrons are laterally confined by micrometer-sized metal pads below the helium. Information is stored in the lowest hydrogenic levels. With electric fields, at temperatures of 10^{-2} kelvin, changes in the wave function can be made in nanoseconds. Wave function coherence times are 0.1 millisecond. The wave function is read out with an inverted dc voltage, which releases excited electrons from the surface.



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Pinning and depinning of a classic quasi-one-dimensional Wigner crystal in the presence of a constriction

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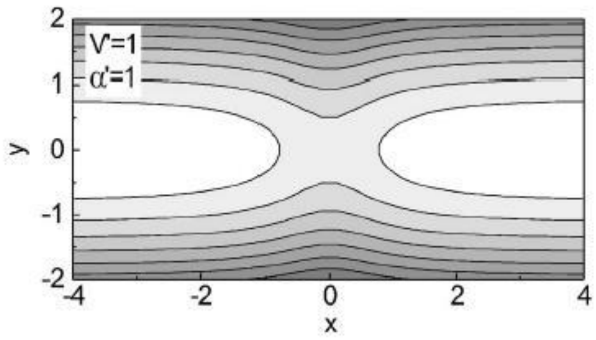
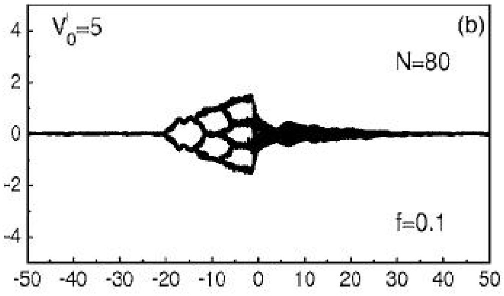
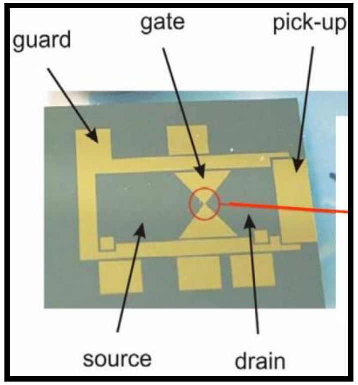
(Received 22 April 2005; revised manuscript received 9 August 2005; published 30 November 2005)





A microchannel point-contact device



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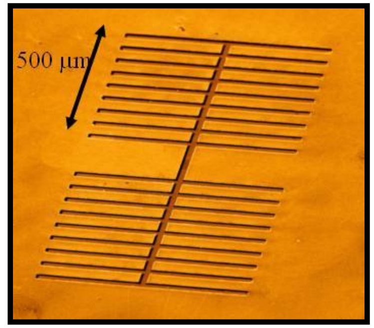

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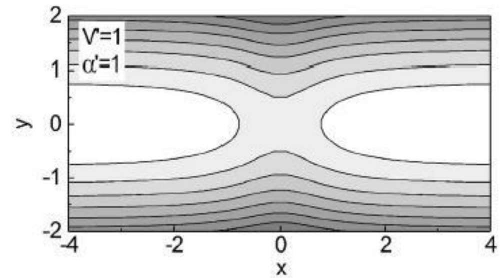


?

We would like to form a point constriction for electrons on helium in a microchannel:

Split-gate samples have been demonstrated for electrons on films.

In microchannel devices electrons retain 'bulk' properties i.e. high mobility, Wigner crystallisation etc.

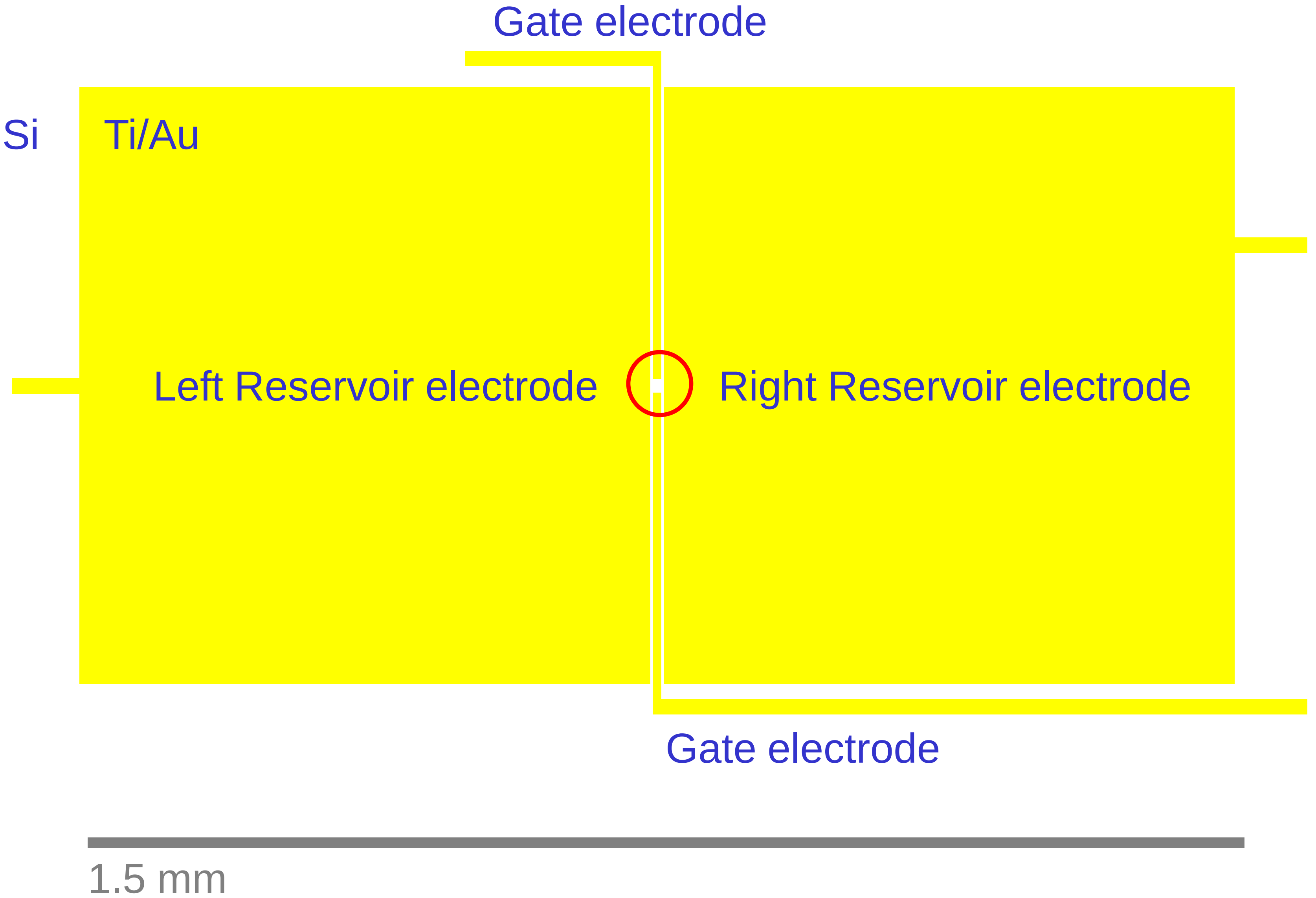
Objectives:

1) Can we realise 1D transport?

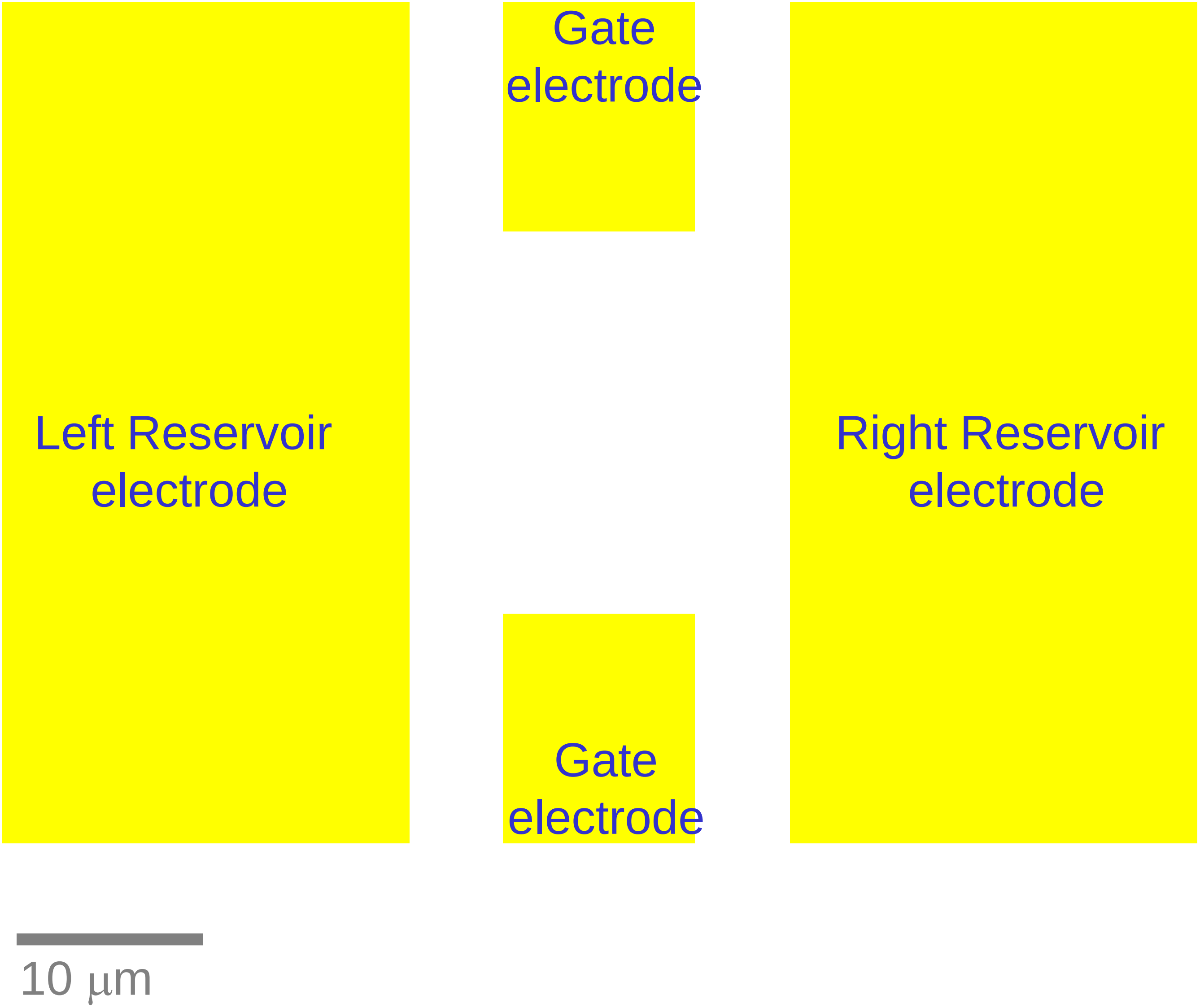
2) Can we observe the quantisation of lateral motion?

3) Can we observe correlation effects?

Layer 1 – UV lithography:



Layer 2 – e-beam lithography:



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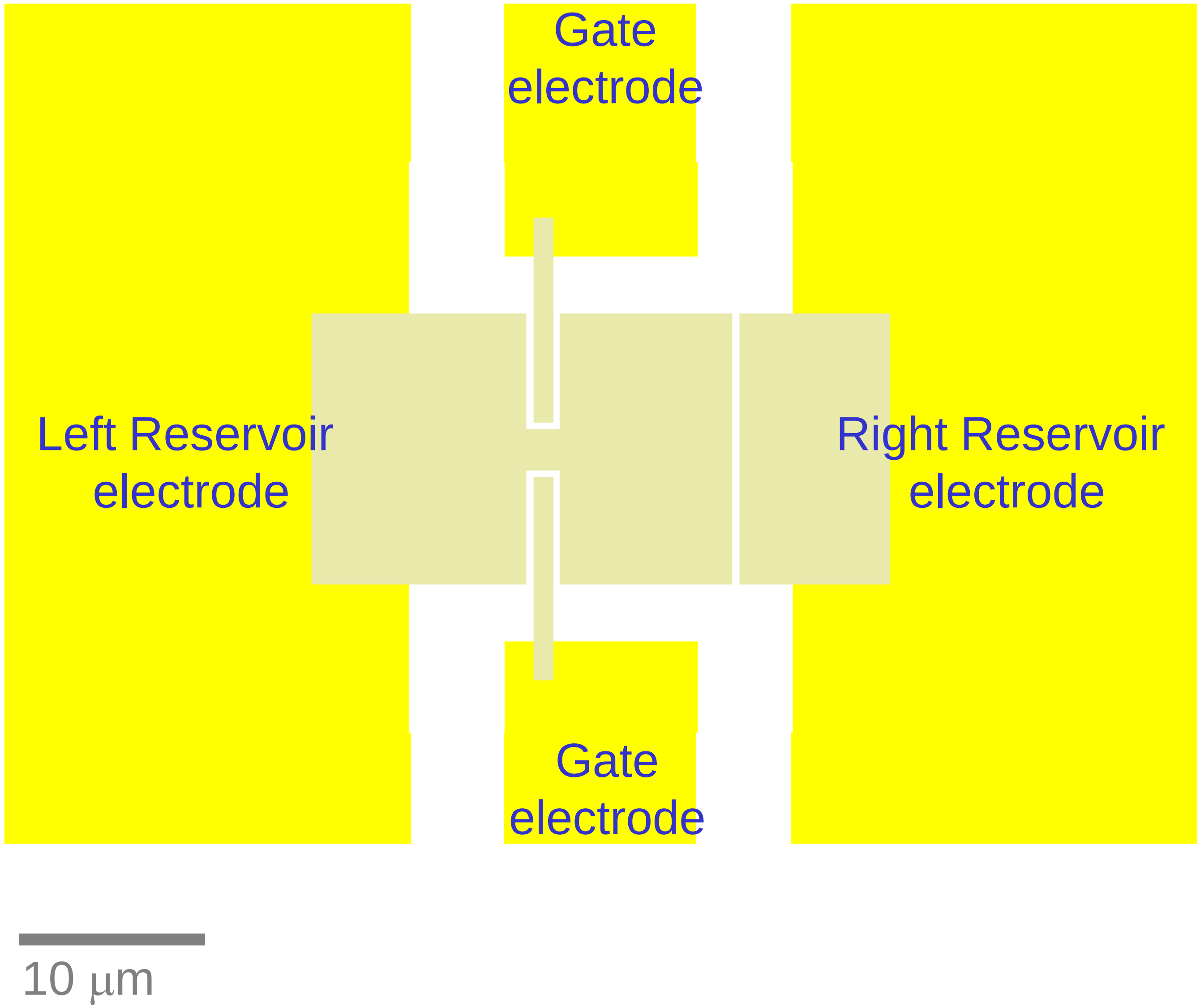
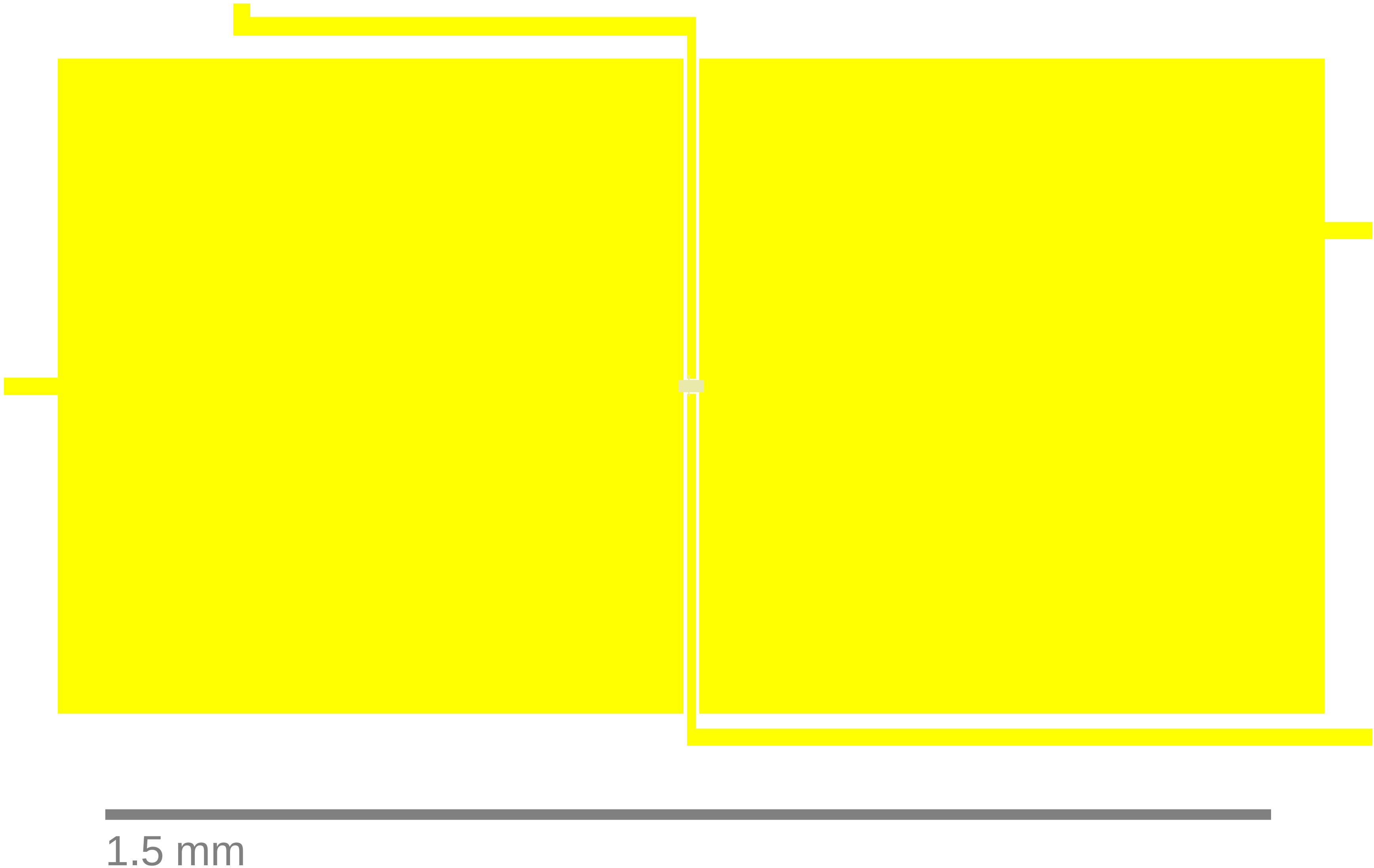
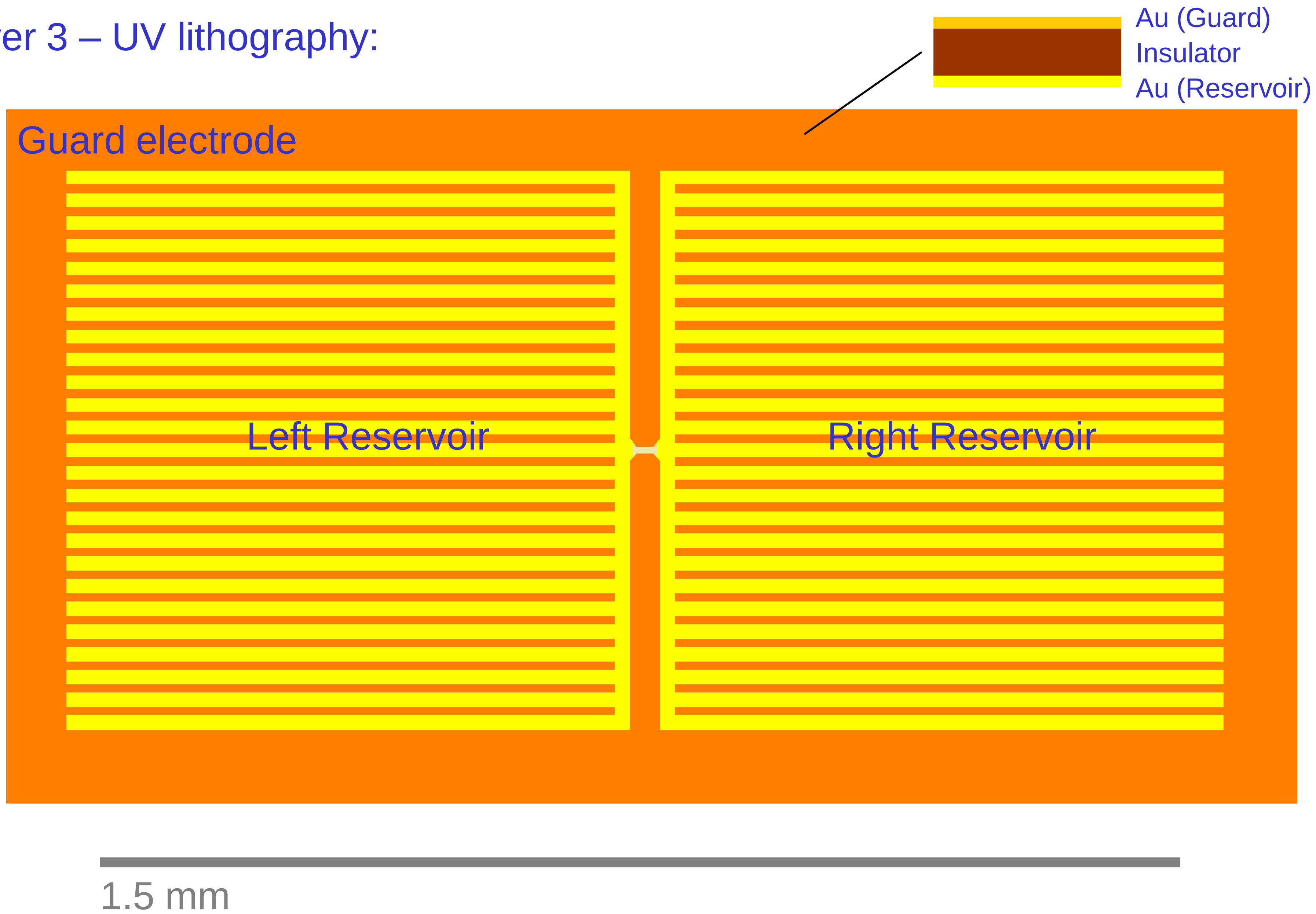
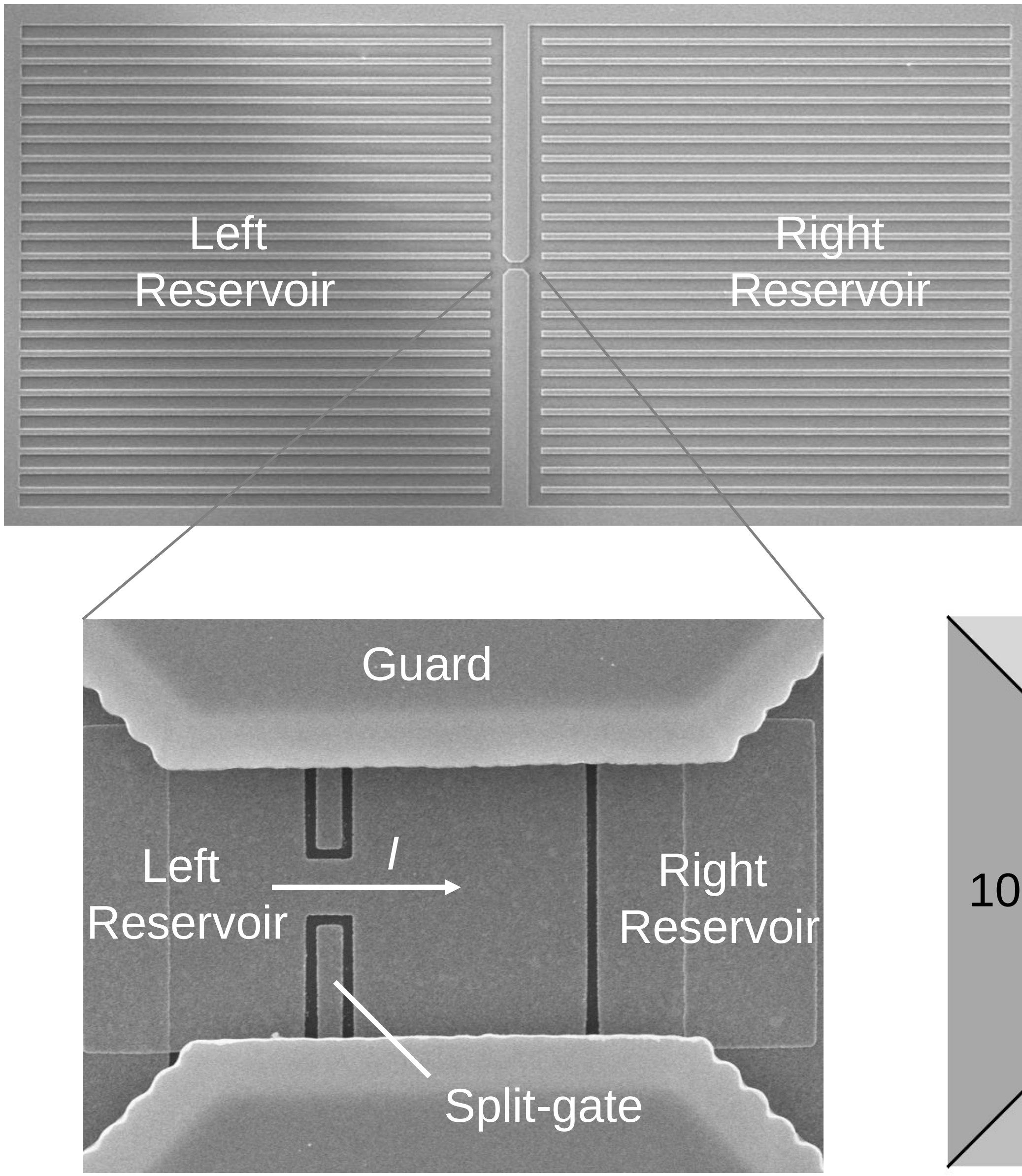


Layer 3 – UV lithography:

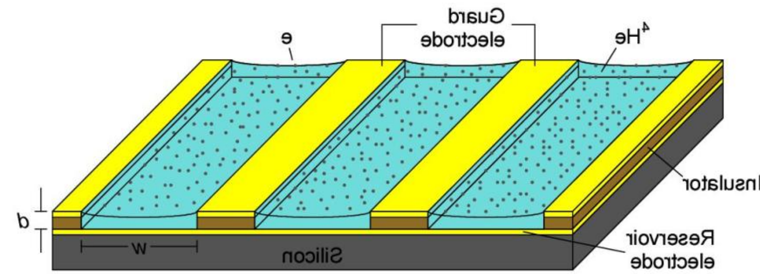


Layer 3 – UV lithography:

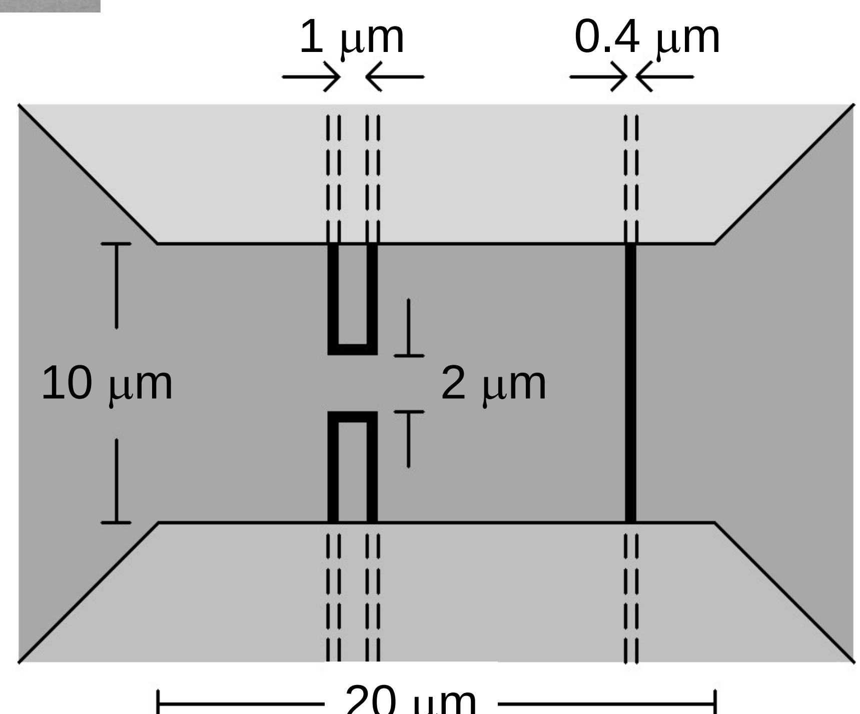




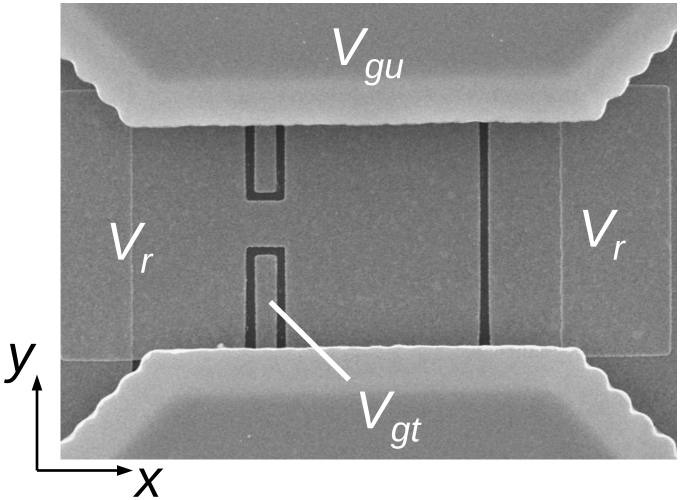
2 sets of reservoirs:



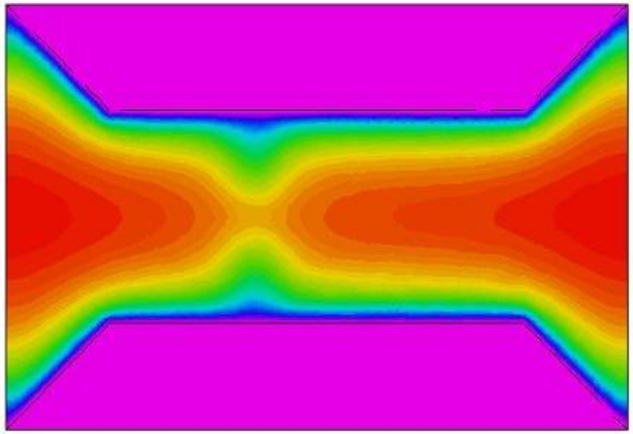
w = 20 μm, d = 1.5 μm



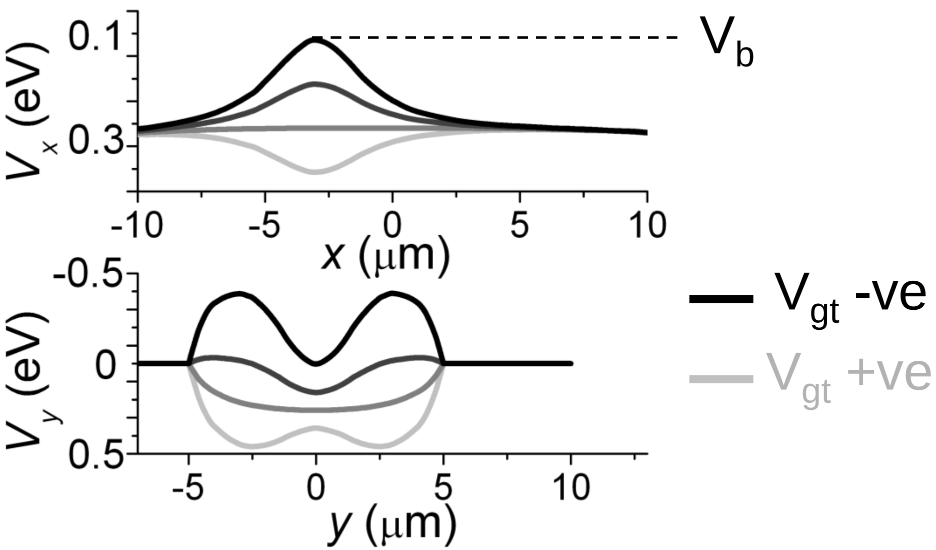
Finite-element modelling shows that a *saddle-point potential* is created at the constriction:



V_{gu} = 0 V
V_{gt} = +0.5 V
V_r = +1 V:



At negative gate voltage we may form a potential barrier between reservoirs:

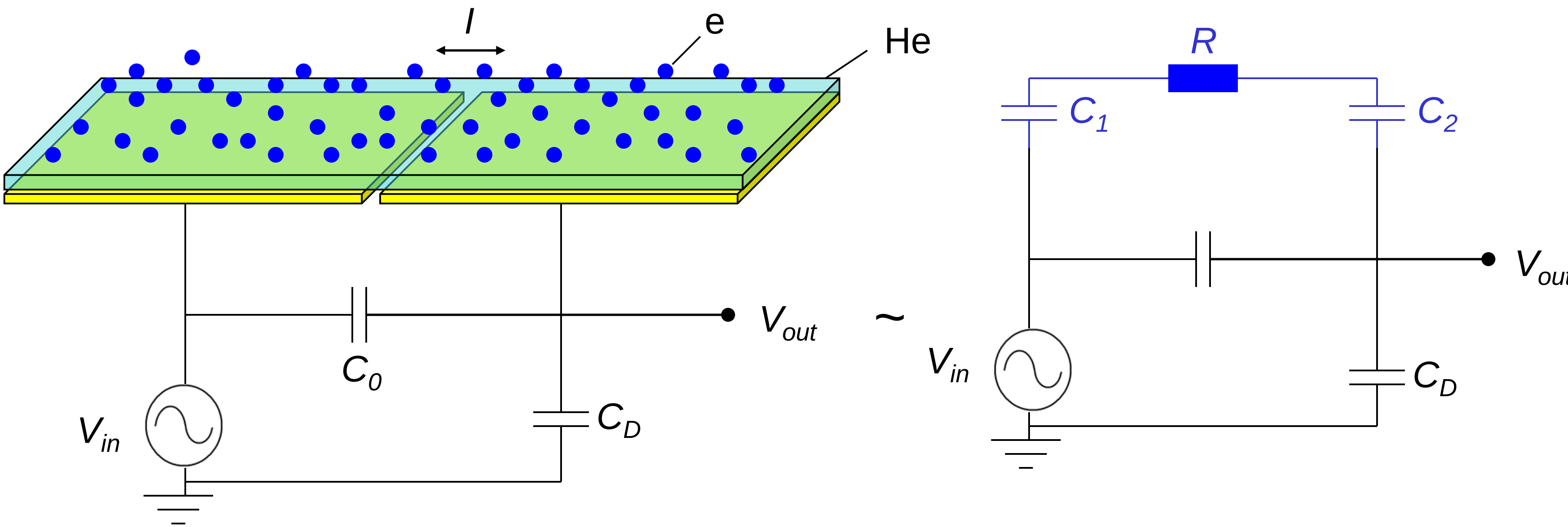


From the model we find:

$V_b = \alpha V_r + \beta V_{gt} + \gamma V_{gu}$

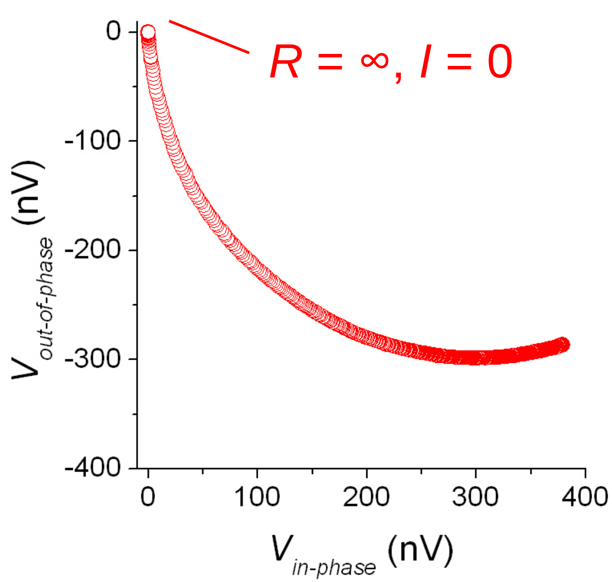
$\alpha = 0.75$, $\beta = 0.10$, $\gamma = 0.15$

T_{Well} ~ 20 GHz ~ 1 K ~ 0.1 meV



Measure V_{out} with lock-in amplifier:

Sweep V_{gt} :



$$\frac{V_{out\text{-}of\text{-}phase}}{V_{in\text{-}phase}} \sim \omega CR$$

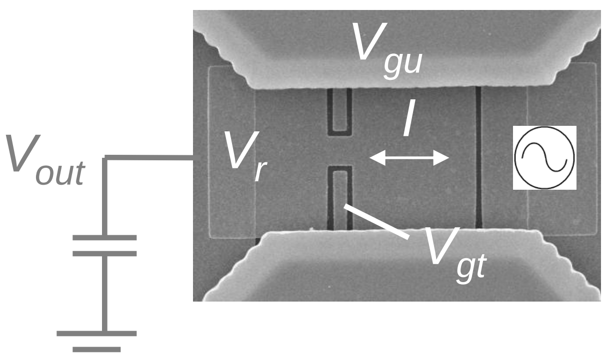
Experimental parameters:

T = 1.2 K

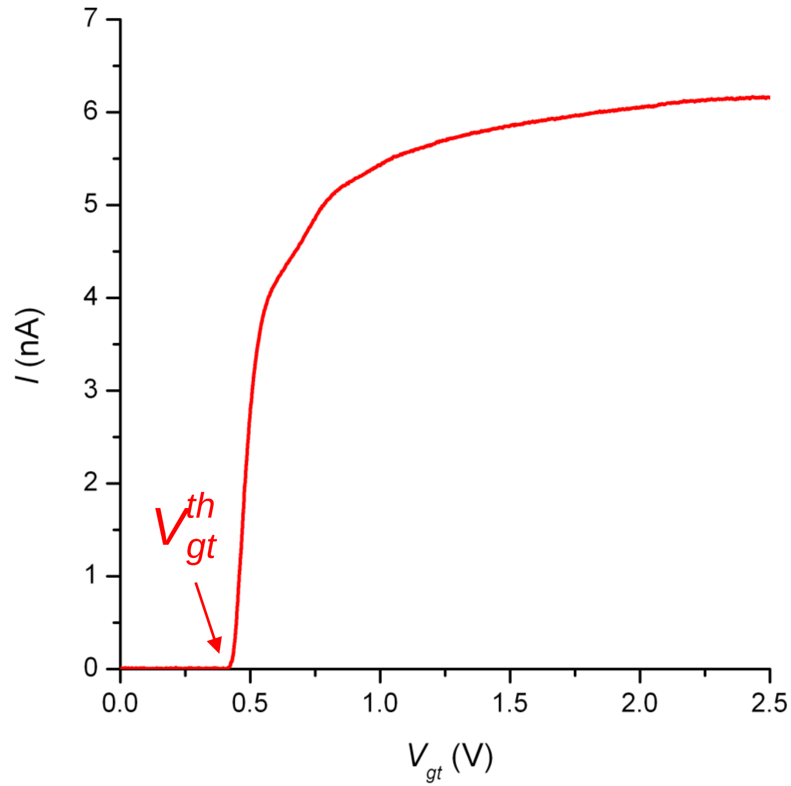
V_r = +1 V, V_{gu} = 0 V

V_{in} = 8 mV_{PP}

f_{in} = 200 kHz

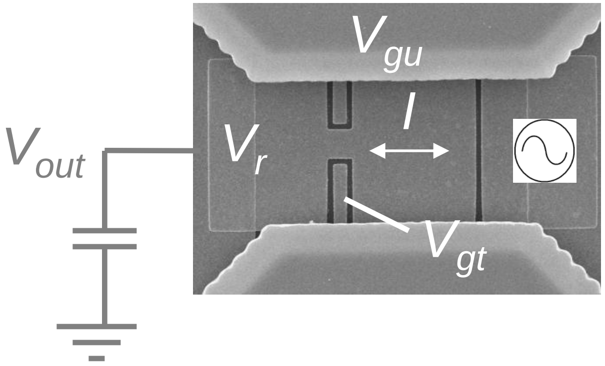


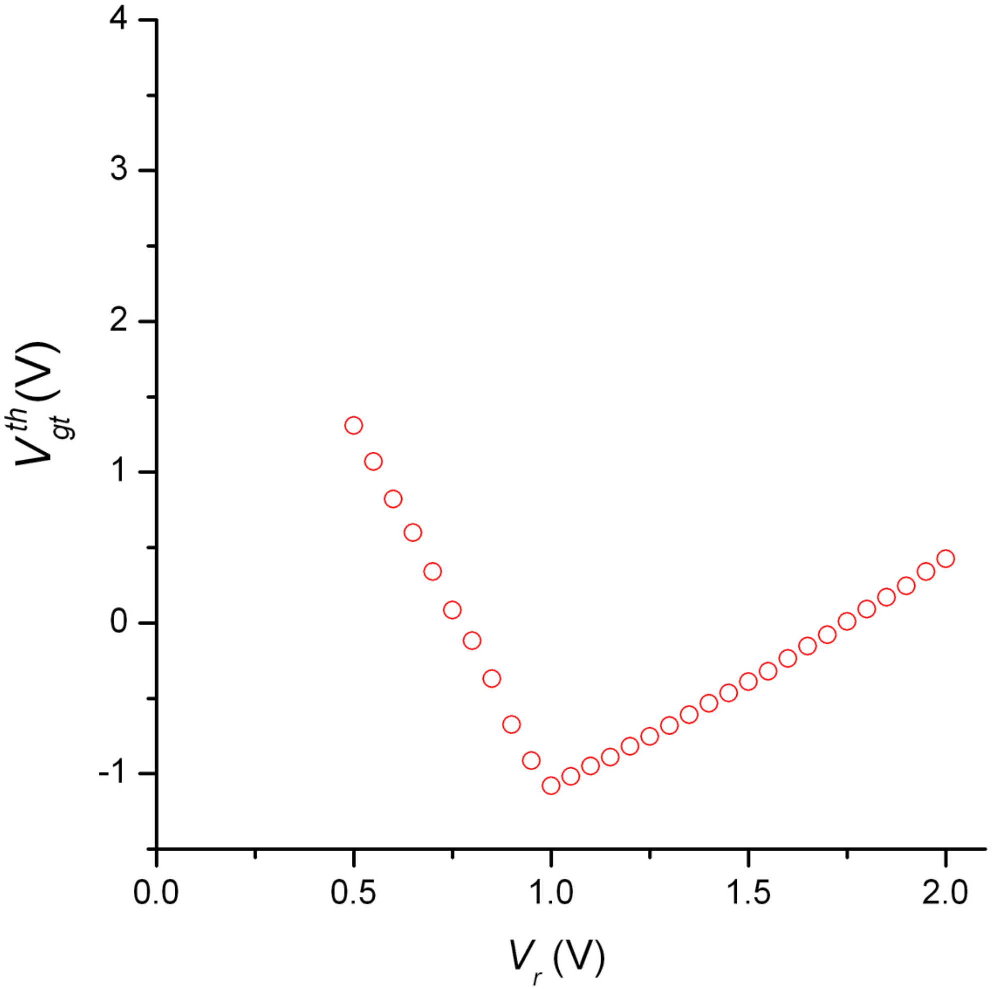
Sweep V_{gt} :



Measure current threshold at different reservoir electrode voltage:

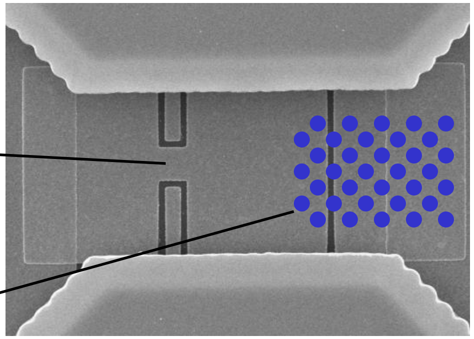
Note: Helium surface is charged at V_r = +1.0 V





V_b depends on the reservoir, gate and guard bias:

$$V_b = \alpha V_r + \beta V_{gt} + \gamma V_{gu}$$



Electron electrochemical potential depends on the reservoir bias and the electron density:

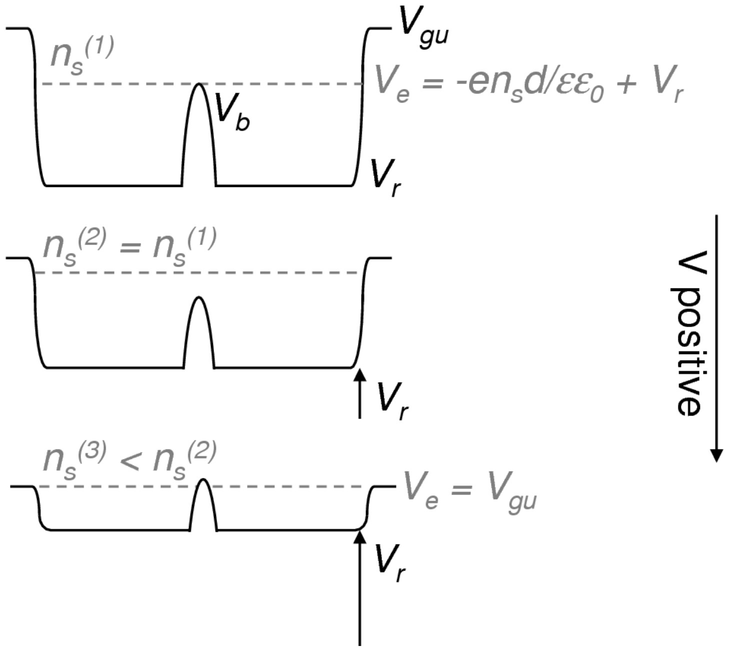
$$V_e = -e n_s d / \varepsilon \varepsilon_0 + V_r$$

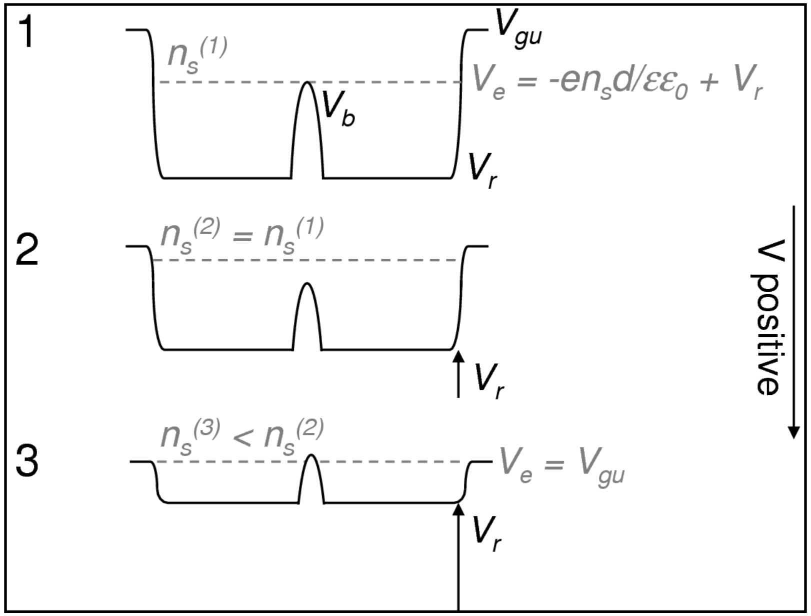
Sweep V_r from positive to negative:

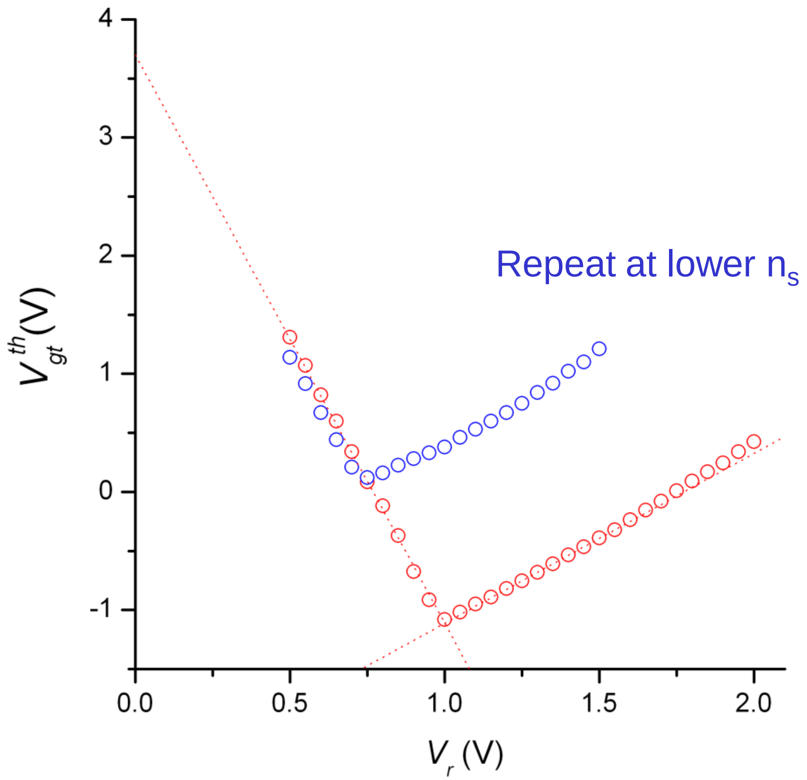
1) 'Pinch-off': $V_b = V_e$

2) Set V_r negative: no change in n_s: Must make V_{gt} more negative to reach 'pinch-off'.

3) As e are lost to the guard V_e remains fixed: Must make V_{gt} more positive to reach 'pinch-off'.





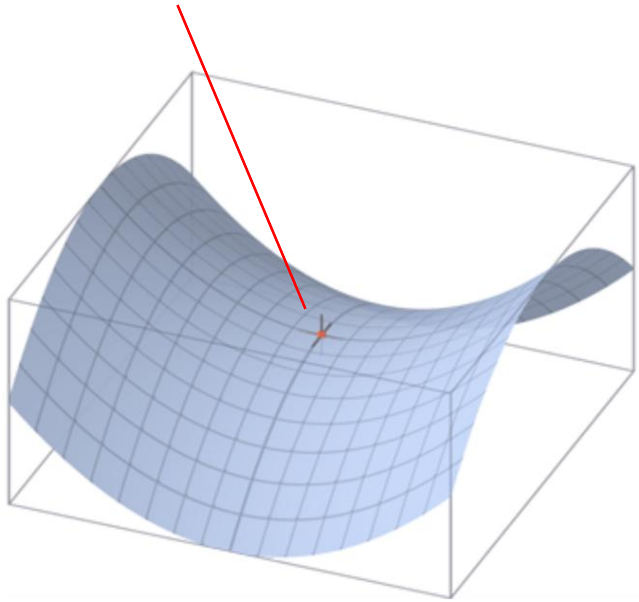


A: $$\frac{-en_sd}{\varepsilon\varepsilon_0} + V_r = \alpha V_r + \beta V_{gt}^{th} + \gamma V_{gu} \longrightarrow \boxed{V_{gt}^{th} = \frac{1-\alpha}{\beta}V_r - \frac{\frac{en_sd}{\varepsilon\varepsilon_0} + \gamma V_{gu}}{\beta}}$$

B: $$V_{gu} = \alpha V_r + \beta V_{gt}^{th} + \gamma V_{gu} \longrightarrow \boxed{V_{gt}^{th} = \frac{-\alpha}{\beta}V_r + \frac{1-\gamma}{\beta}V_{gu}}$$

$\alpha+\beta+\gamma = 1$: Solve for α,β,γ…

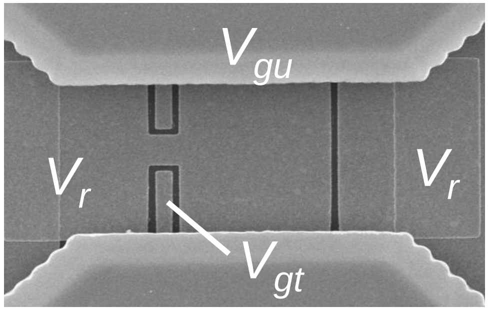
$$V_b = \alpha V_r + \beta V_{gt} + \gamma V_{gu}$$



Coupling Constant	Model	Measured
α	0.75	0.77
β	0.10	0.16
γ	0.15	0.07

Good agreement…

Electrons are indeed above the reservoir electrode, between the split-gate:

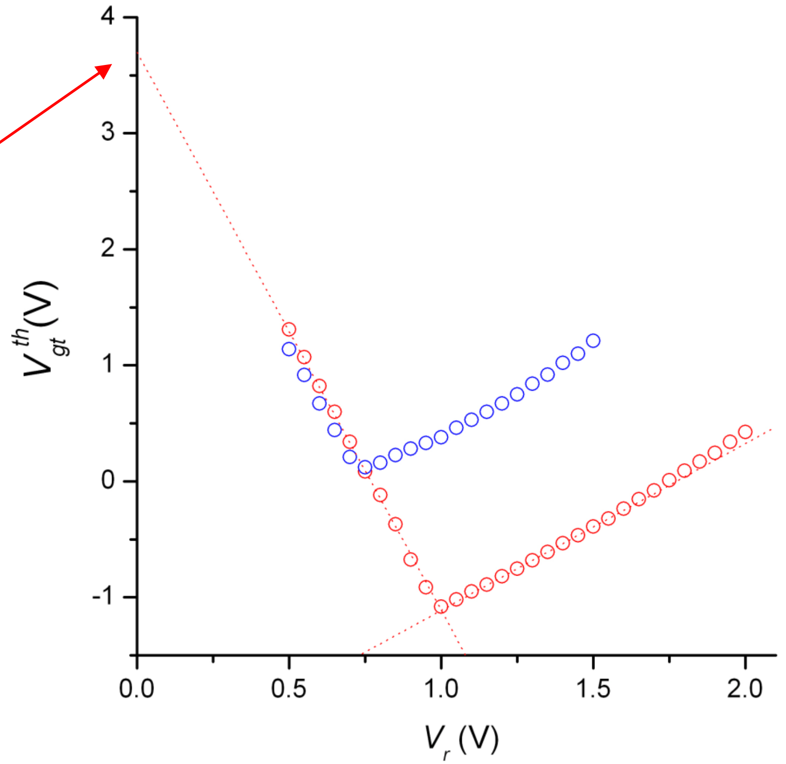


Experimentally we set V_{gu} = 0 V.

But we see that the effective potential is positive:

$$V_{gt}^{th} = \frac{-\alpha}{\beta} V_r + \frac{1-\gamma}{\beta} V_{gu}$$

→ $V_{offset,gu} \sim +0.62$ V



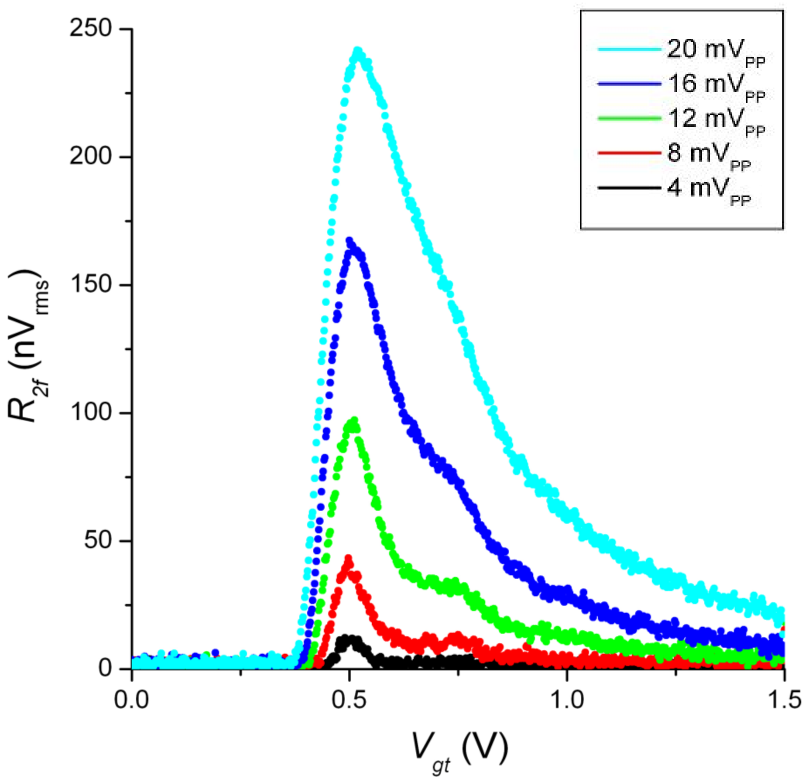
Potential offsets could be caused by image charging, contact potential differences, thermoelectric effects, substrate charging..?

Note – This offset was not observed in other devices!

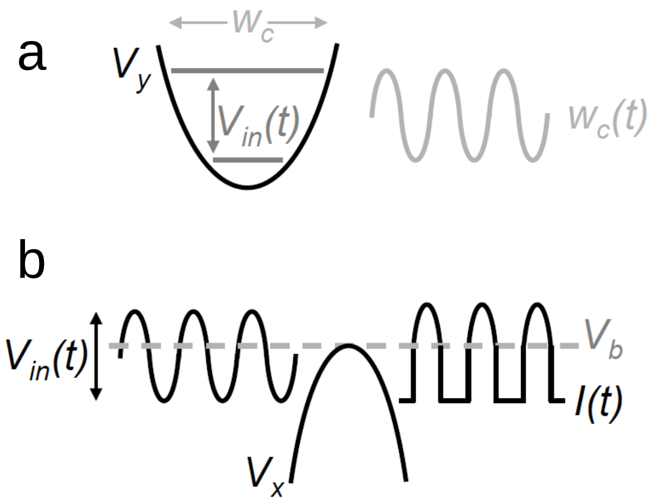
Measure 2nd harmonic component of current signal (f_{2f} = 400 kHz):

Fourier: R_{2f} = 0 if the current is sinusoidal

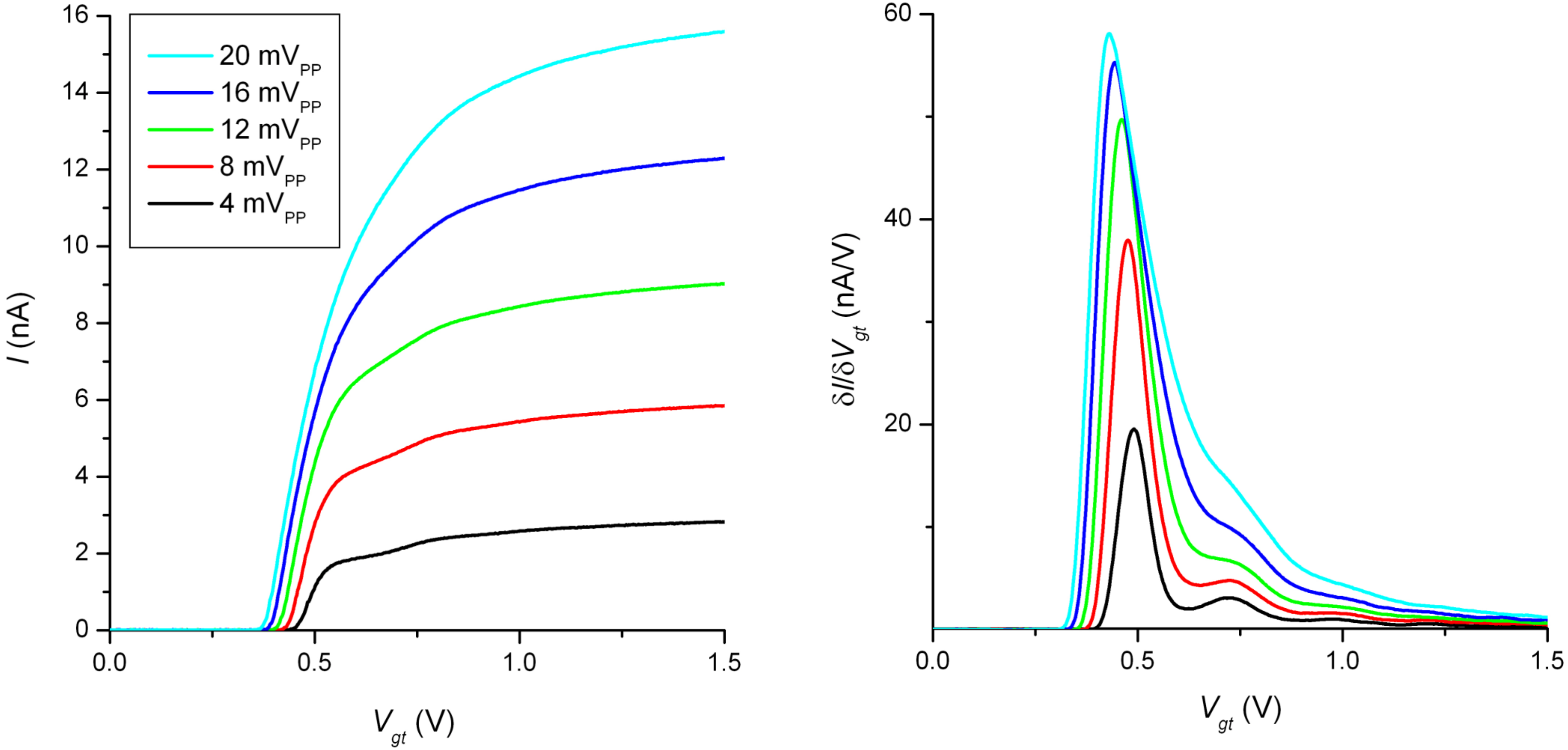
Gives a measure of signal distortion



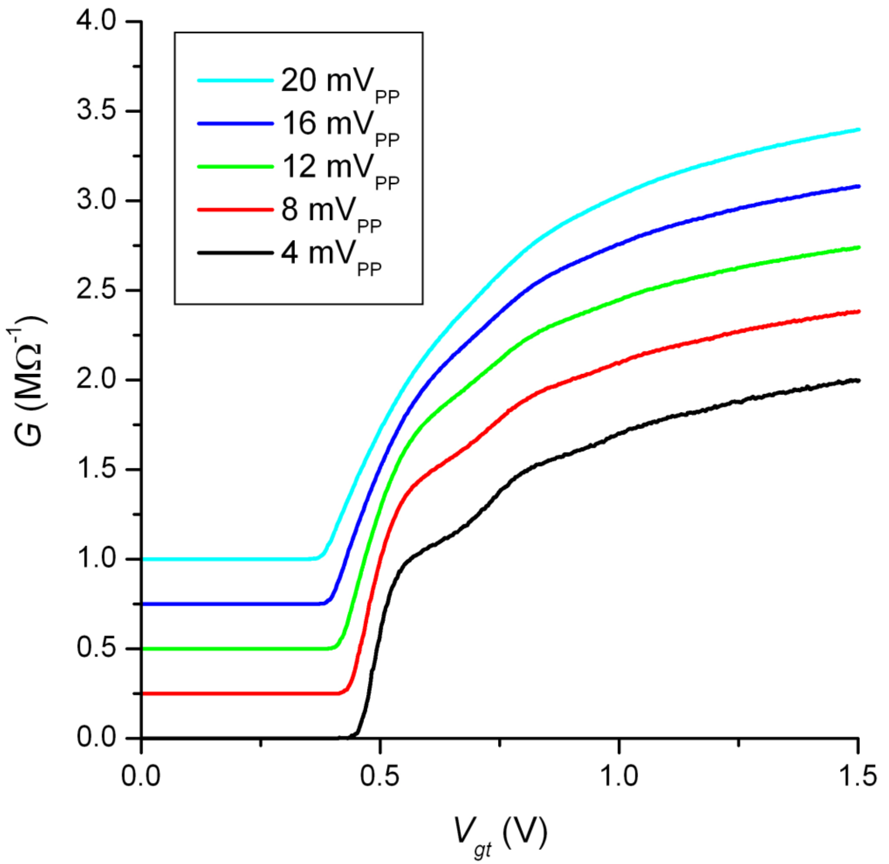
We would expect transport a) through a parabolic potential or b) across a potential barrier to show strong distortion:

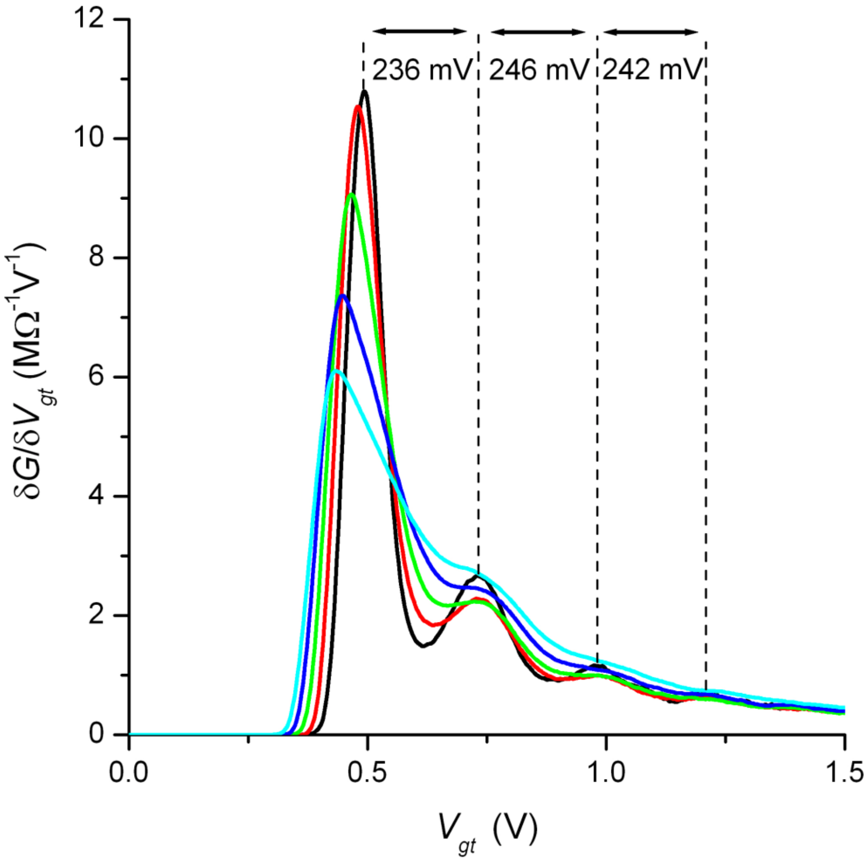


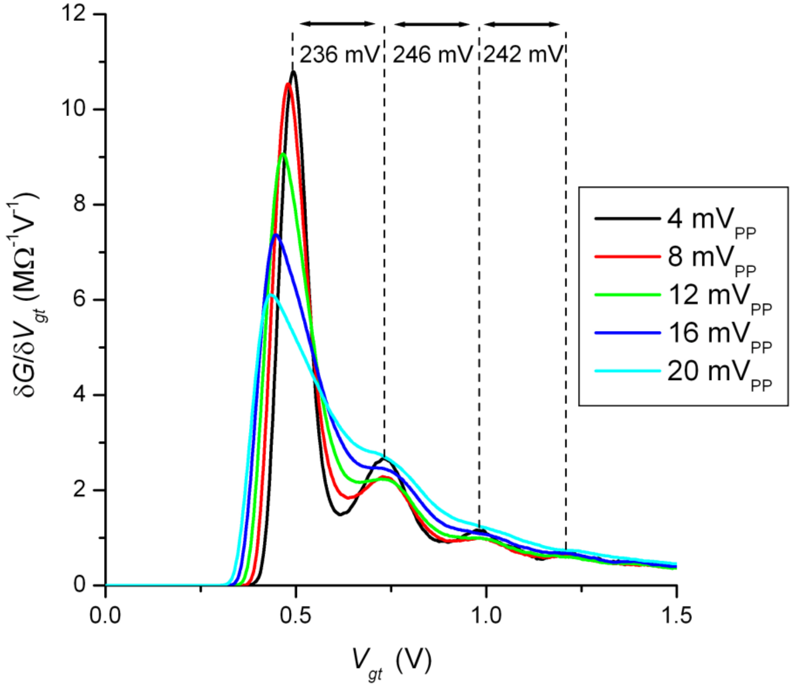
With thanks to Prof. M. Dykman!


16
14
12
10
8
6
4
2
0
I (nA)
20 mVPP
16 mVPP
12 mVPP
8 mVPP
4 mVPP
0.0
0.5
1.0
1.5
Vgt (V)
60
40
20
δI/δVgt (nA/V)
0.0
0.5
1.0
1.5
Vgt (V)

Structure in G vs V_{gt}..?







ΔV_{gt} = 240 mV → ΔV_b = 24 mV

Confinement energy is much smaller:

T_{well} ~ 1 K ~ 0.1 meV

Structure still discernable at V_{in} = 20 mV_{PP}

Very simple calculation:

Channel width $w = c_1 V_{gt}^{1/2}$

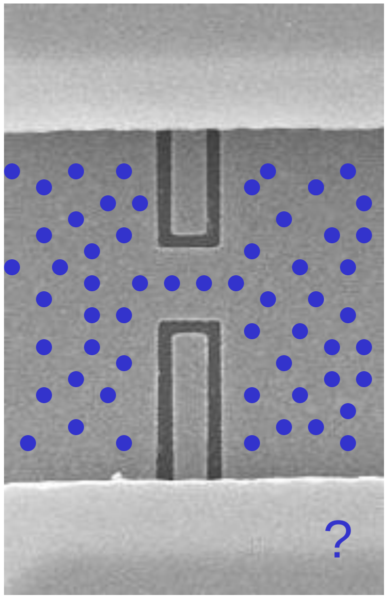
Potential depth $V_{well} = c_2 V_{gt}$

$d_{e\text{-}e} \sim (\varepsilon\varepsilon_0 \cdot c_2 V_{gt} / ed)^{-1/2}$

Electron rows across channel:

$n_l = w/d_{e\text{-}e} = c_1 (\varepsilon\varepsilon_0 \cdot c_2 / ed)^{1/2} V_{gt}$

$\Delta V_{gt,calc}$ = 221 mV



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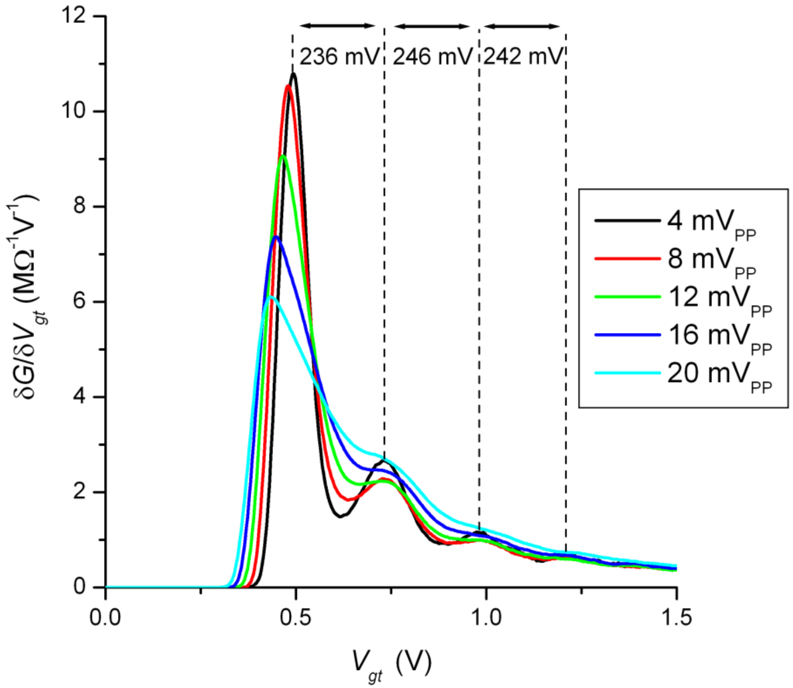

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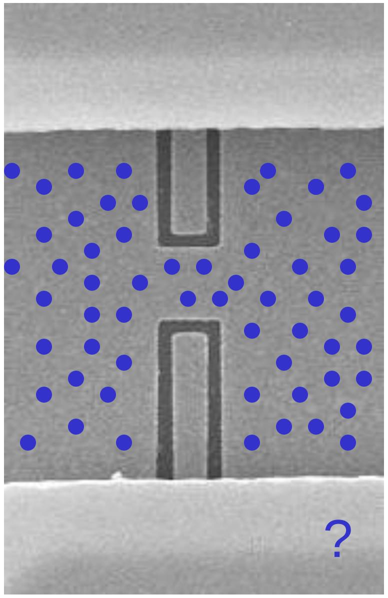

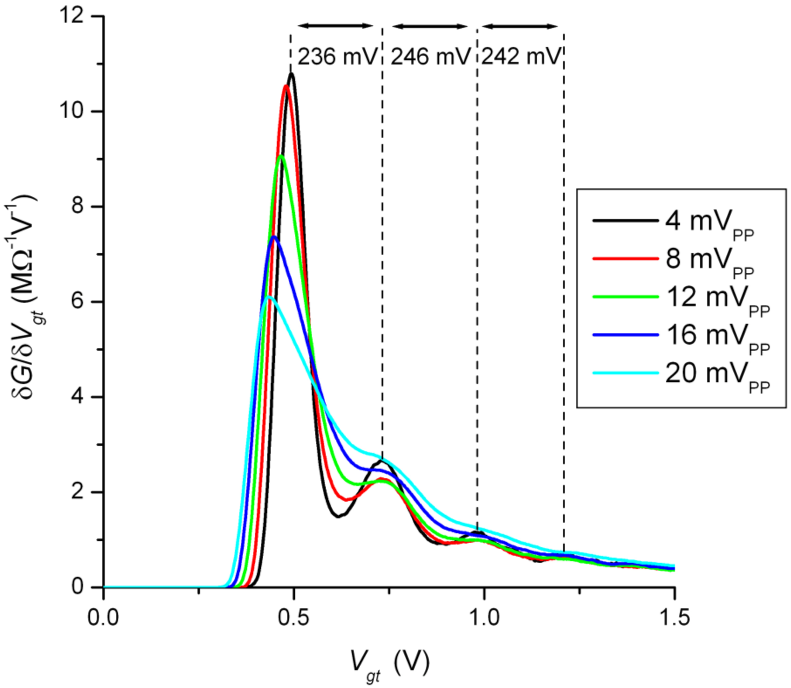

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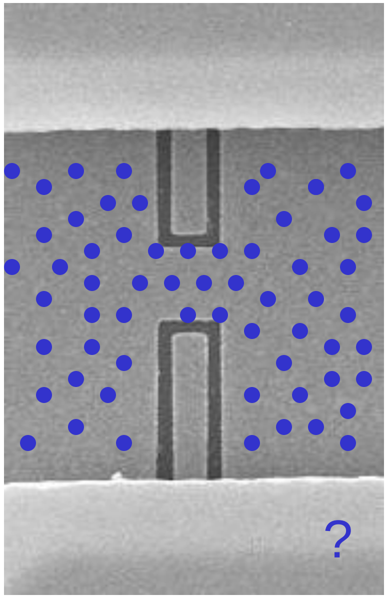
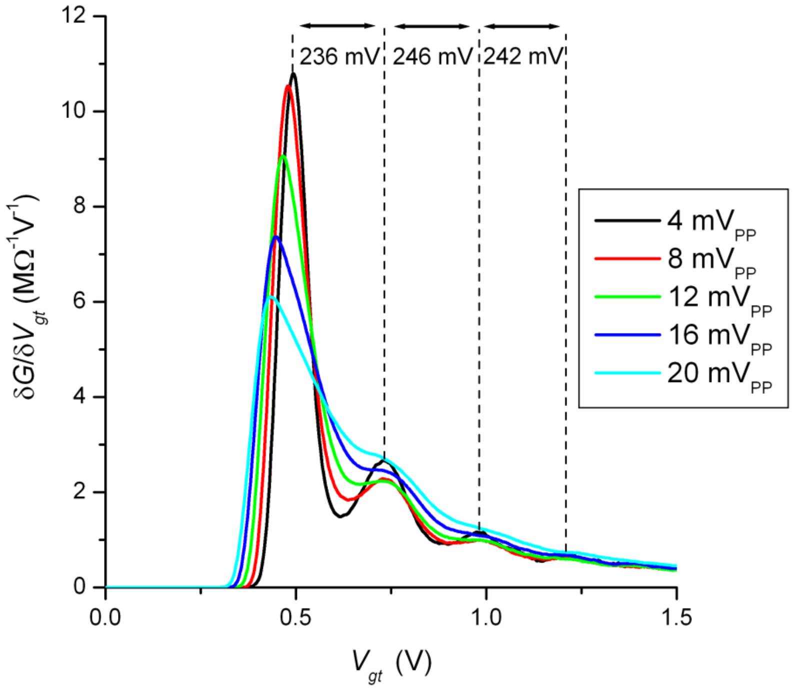


Structure in G vs V_{gt}..?



ΔV_{gt} = 240 mV → ΔV_b = 24 mV

Confinement energy is much smaller:

T_{well} ~ 1 K ~ 0.1 meV

Structure still discernable at V_{in} = 20 mV$_{PP}$

Very simple calculation:

Channel width $w = c_1 V_{gt}^{1/2}$

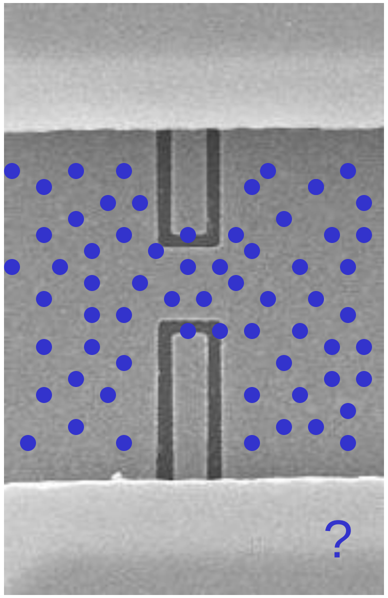
Potential depth $V_{well} = c_2 V_{gt}$

$d_{e\text{-}e} \sim (\varepsilon\varepsilon_0 \bullet c_2 V_{gt} / ed)^{-1/2}$

Electron rows across channel:

$n_l = w/d_{e\text{-}e} = c_1 (\varepsilon\varepsilon_0 \bullet c_2 / ed)^{1/2} V_{gt}$

$\Delta V_{gt,calc}$ = 221 mV



Conclusions

- We have measured the transport properties of electrons on helium in a microchannel point-contact device.
- The potential profile of the device has been characterised in detail.
- The transport threshold depends on the electron density n_s.
- Potential offsets are (still) a problem.
- Measuring distortion gives us additional information.
- We see signs of Coulomb interaction affecting the transport properties of the electron liquid.
- See our poster for more details including temperature dependence and transport of the electron solid.

Thank you