Investigation of Phonon Emission Modes in a Channel-Gated GaAs/AlGaAs Finger-Gate Electron Pump

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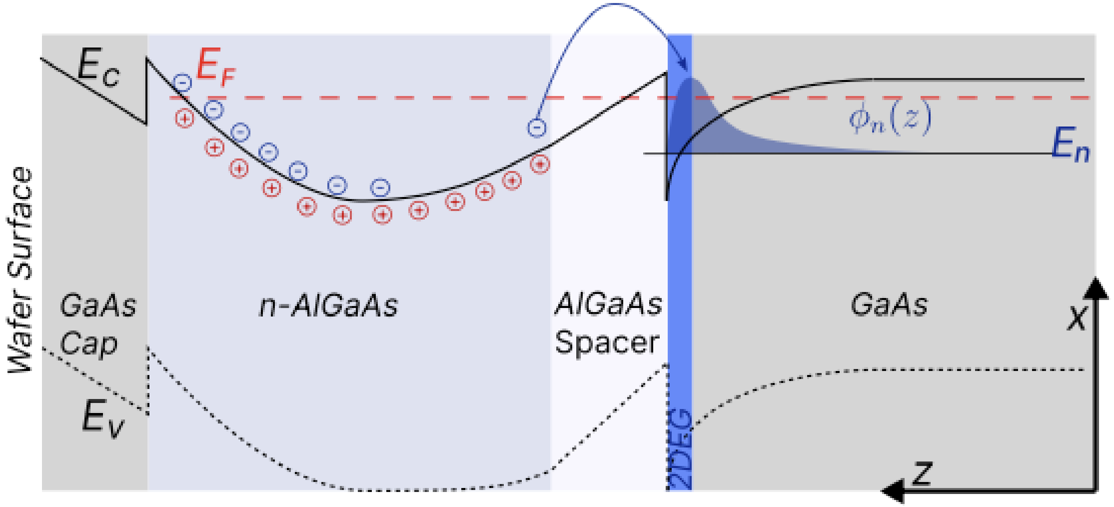
Low dimensional materials and heterostructures

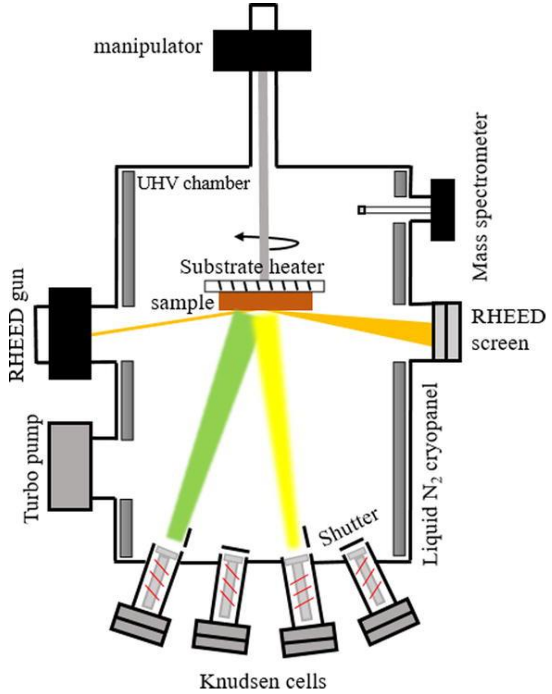
To access individual electrons, we create create a low dimensional system.

Heterostructure wafers are grown using molecular beam epitaxy to precisely layer the desired materials layered on top of one another.

Through a process called modulation doping, a given layer is doped with charge carriers. When the heterostructures are cooled to very low temperatures these charge carriers migrate to a different region.

Due to the materials chosen the region where the charge carriers are confined forms a potential well once cooled. The electrons confined then become quantized in the z-direction and are only free to move in the x and y directions. This is the formation of the 2-dimensional electron gas (2DEG)





What is an electron pump

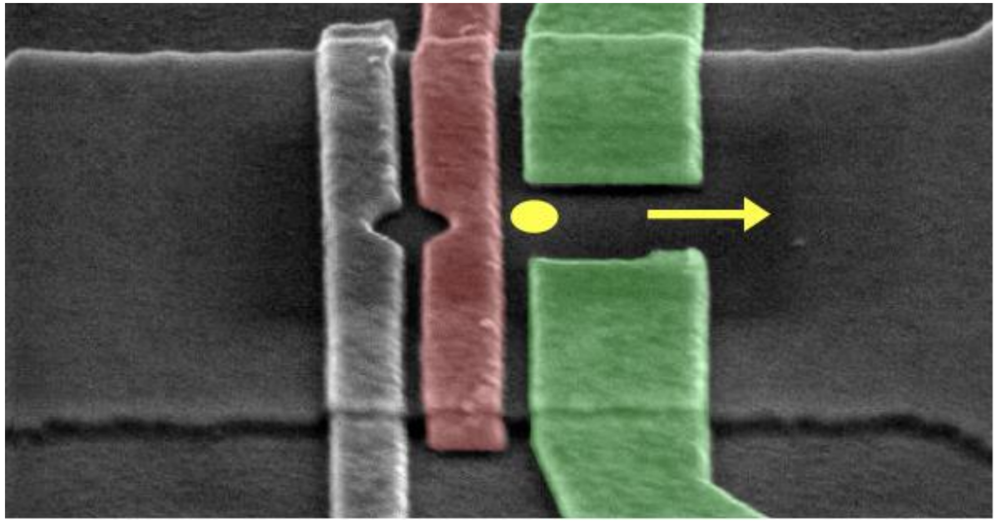
The goal of the electron pump is to reliably deliver an on demand source of electrons at a high degree of accuracy.

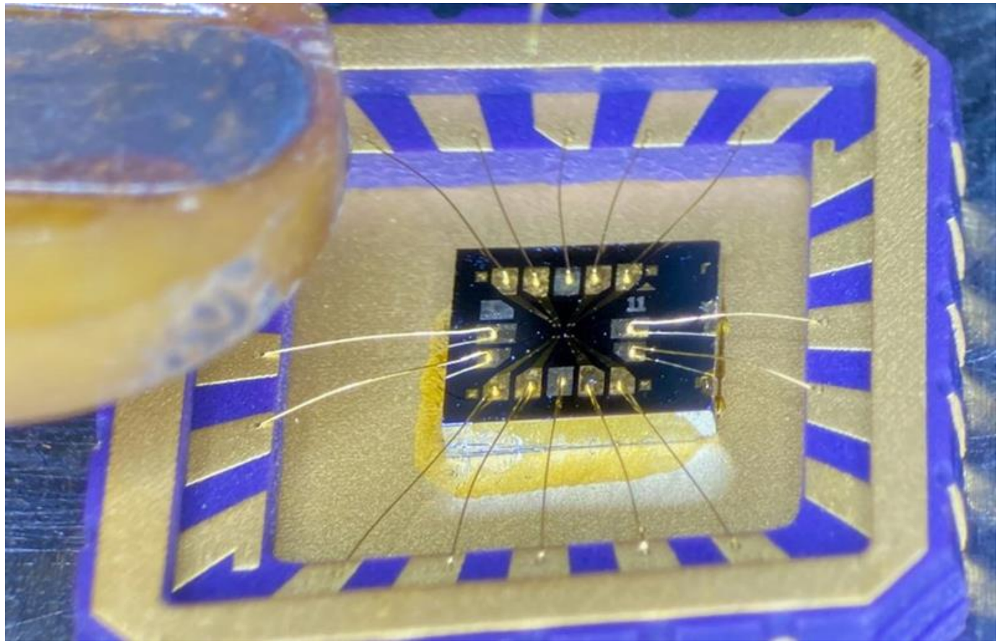
An electron pump consisted of an etched 1D channel created used electron beam lithography along with two top gates. Traditionally one of two geometries.

- Finger gate – Finger gate (FF)
- Finger gate – Split gate (FS)

Both geometries follow the the same philosophy of pump operation.

- The exit barrier which is the second gate is set at a fixed DC voltage value
- The entrance gate is set at a fixed voltage and an additional AC voltage is applied.
- The 0D quantum dot is repeated created and destroyed Confining and ejecting the electron.

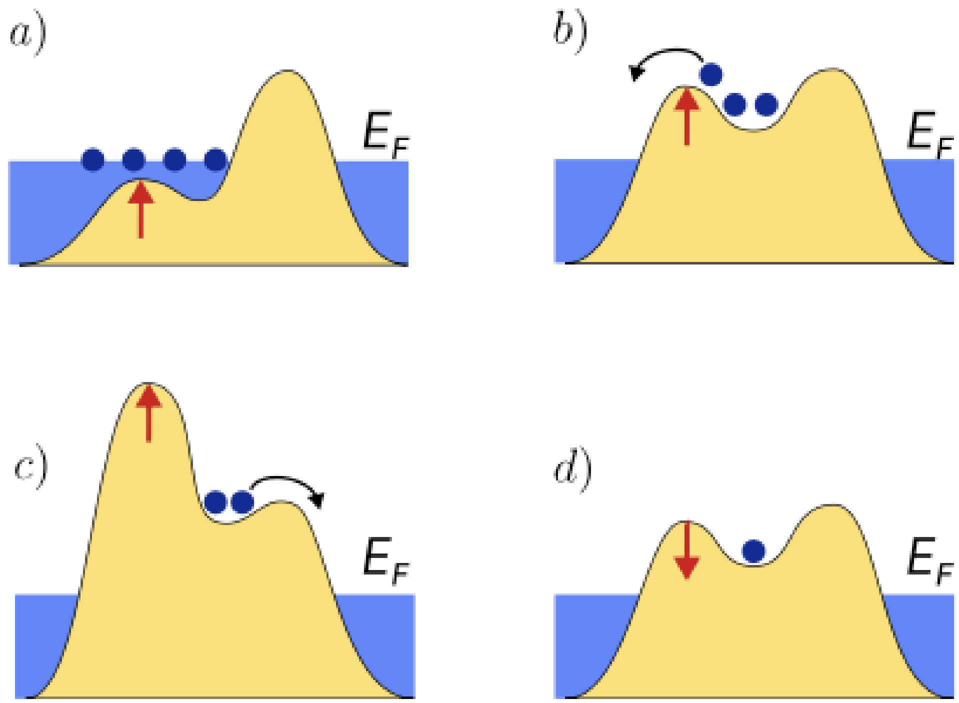




Capture Confinement and ejections

This RF voltage causes the entrance barrier to oscillate around its fixed position. This results in the three distinct stages of pump operation as electrons tunnel through the potential barriers

- Capture
- Confinement
- Ejection



Capture (a)
The barrier dips to its lowest point bellow the Fermi sea and captures one or more electrons.

Confinement (b)
As the barrier rises the electrons become confine within the quantum dot. The electrons arrange themselves as to minimize their coulomb-coulomb interaction within the dot.

Ejection (c)
The barrier rises which in turn causes the dot to rise and the electron gets ejected over the exit barrier.

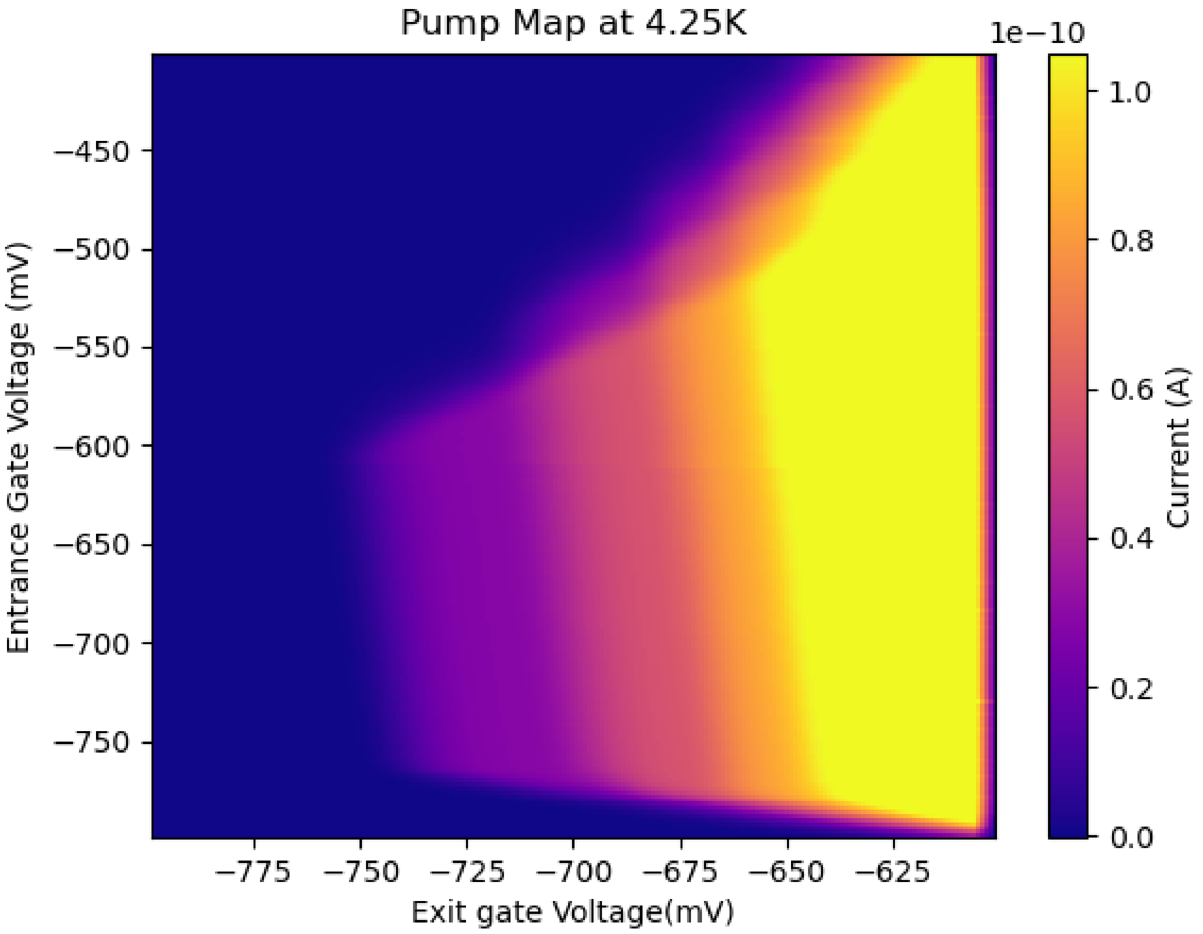
Pump Operation

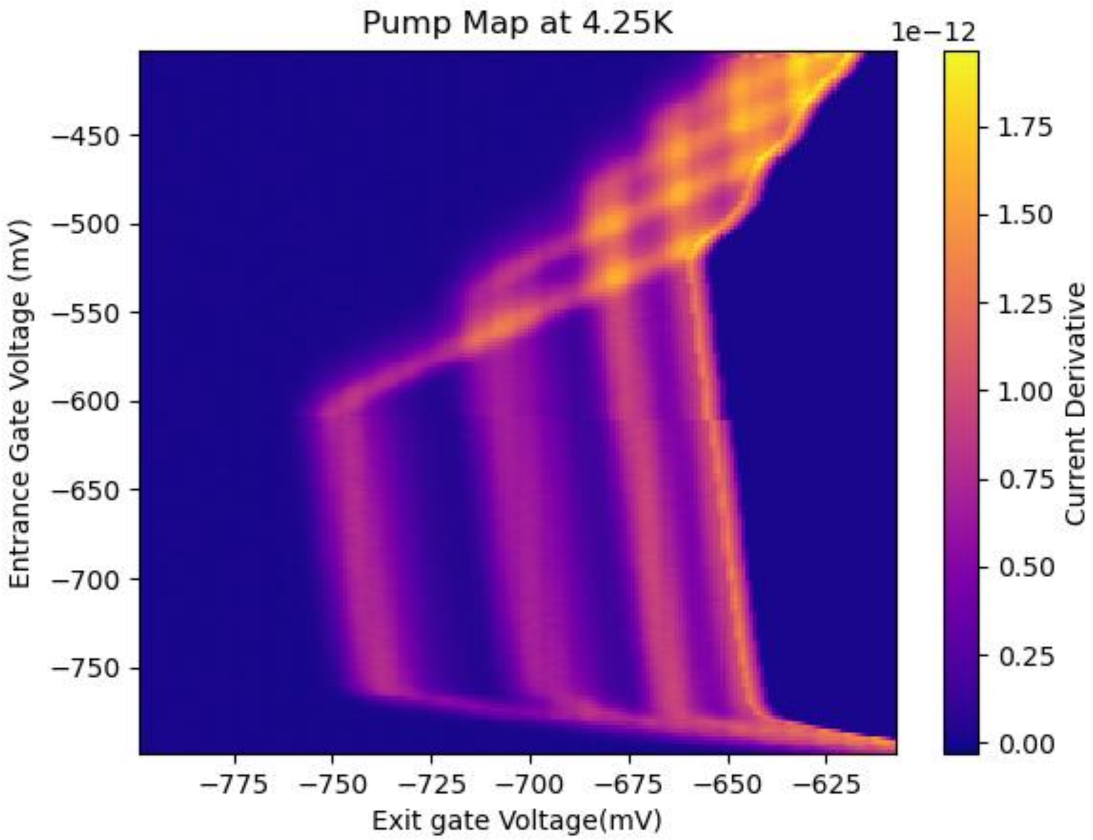
When describing the dynamics of an electron pump it is often useful to use classical language such as ‘picking up’ and electron. But what is really occurring is that electron is tunneling through the potential barrier

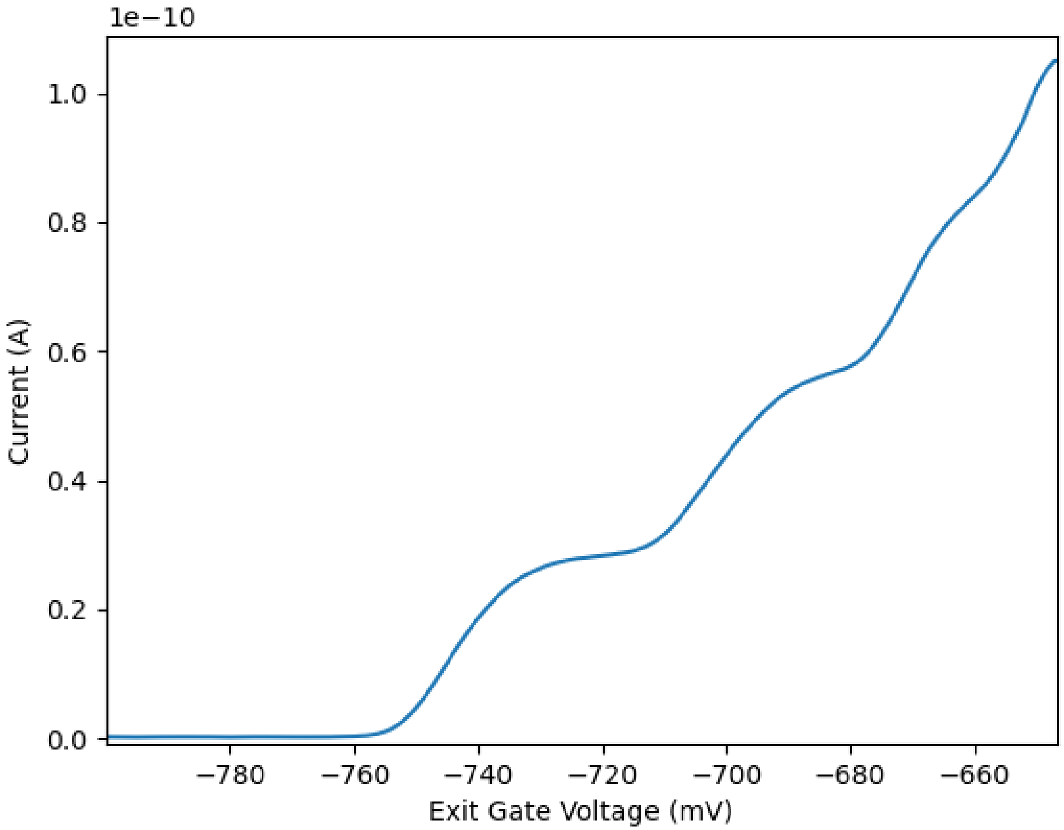
The behaviour and the dynamics of confinement with the dot and what occurs as the dot is being formed are not well understood in the field. There are a few basic principles taking during the attempt to model the behaviour and during the measurement process.

Measurement
-Measuring the current (One electron ejected? Two?)
-Measuring the energy of these electrons.

Modeling
-The first being to treat the confinement as quantum harmonic oscillator.
-Tunneling of the electrons into the dot. Back out of the dot into the source and out the other side into the drain.




Pump Map at 4.25K
1e−12
−450
−500
−550
−600
−650
−700
−750
Entrance Gate Voltage (mV)
−775
−750
−725
−700
−675
−650
−625
Exit gate Voltage(mV)
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Current Derivative


1e−10
1.0
0.8
0.6
0.4
0.2
0.0
Current (A)
−780
−760
−740
−720
−700
−680
−660
Exit Gate Voltage (mV)

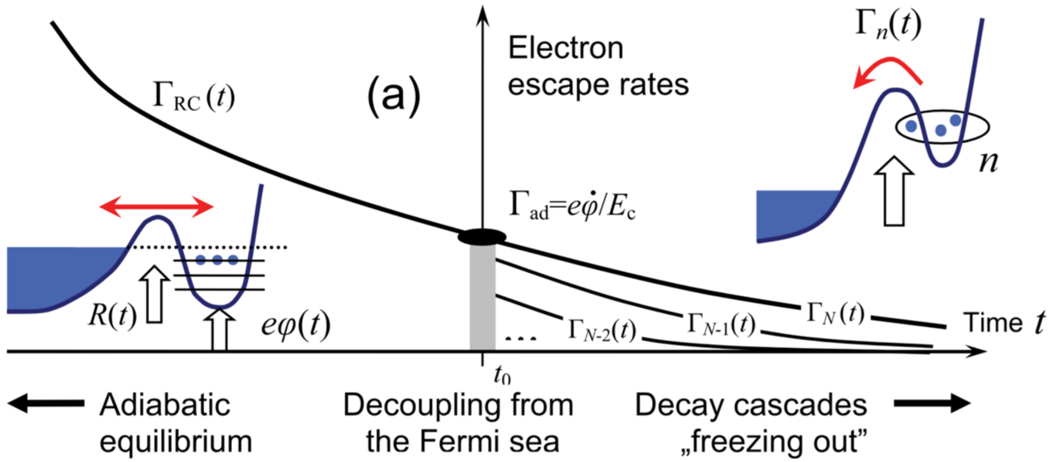
Current fitting model

The potentials involved in created a dynamic quantum dot are time-dependent electrostatic potentials .

- Impossible task to model the dot analytically
- Numerical methods to produce a model

Proposed in 2010 by Kaschcheyevs and Kaestner the model is is named the Universal Decay Cascade (UDC) [1]. The UDC model is based on the stochastic tunnelling rate into the dot and the back-tunneling rate of electrons escaping the dot during capture. The model assumes that all electrons are captured and ejected.

The UDC model is limited in that it has parameters which don't have physical meaning.



$$P_n(\infty) = e^{-X_n} \prod_{m=n+1}^{N} (1 - e^{n})$$

$$X_n = \exp\left(-\alpha_n V + \sum_{i=1}^{n} \delta_i \right)$$

$$I = ef \sum_n n P_n(\infty)$$

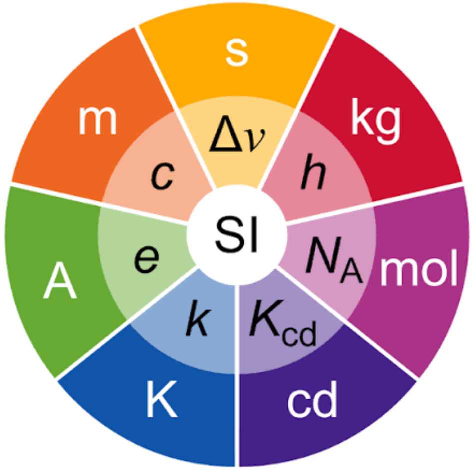
Why?

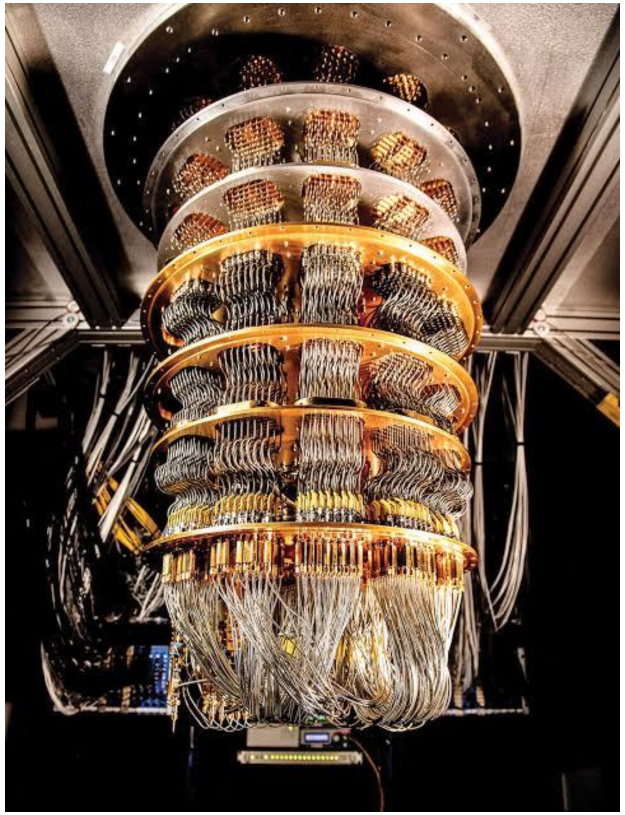
- Understanding the scattering dynamics and processes and the effects on things such as coherence times

- On demand source of electrons can provide electrons into a system for use in devices doing spin manipulation of the electrons.

- Understanding the fundamental behaviours of electrons in the pump and how these behaviours influence the accuracy of pumping

-Advance understanding of the electron pump in aid of the goal of possibly using it to define the standard for the ampere





What are we doing in this device?

With this being said, what are we trying to achieve in our measurements?

- Ejecting the electrons from the pump into the two-channel region
- Measuring the current flowing into each channel to determine the path of the electrons at a given channel gate voltage
- Relate the voltage applied to the gates to an energy scale for the ejected electrons
- Use this information to determine the pump dynamics
- (Eventually) Determine the timing of the electrons repeating the experiment done in *Fletcher et al* [2]

What are we measuring?

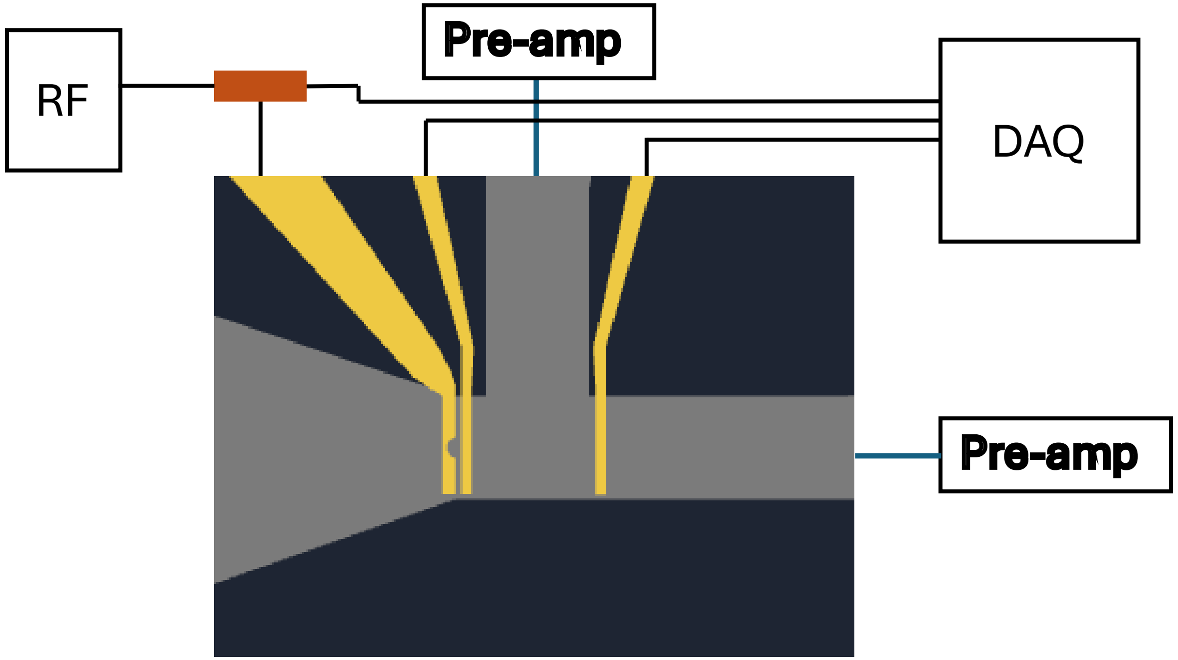
Accessing the 2 dimensional system requires two things

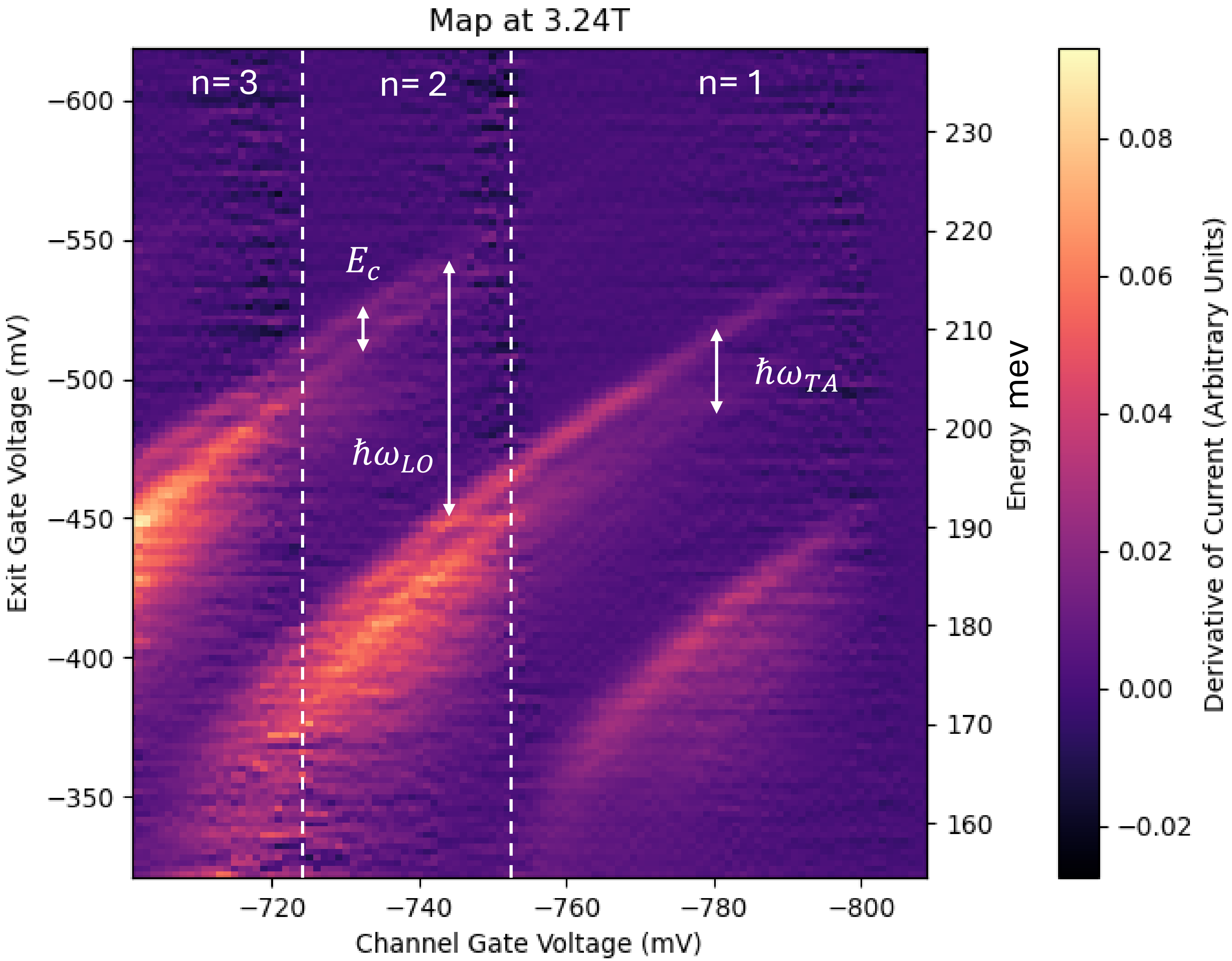
- Very low temperatures (2DEG forms at ~4K)
- Low noise and precise instrumentation

We make use of a dilution refrigerator to reach temperatures on the order of 70mK during pump operation and measure the current with two low noise current to voltage pre- amplifiers

A 16-bit DAQ is used to supply voltages to the gates. With the AC RF signal coming from the function generator coupled to a DC voltage using a bias T.

The pump was operated in the absence of a source drain bias.

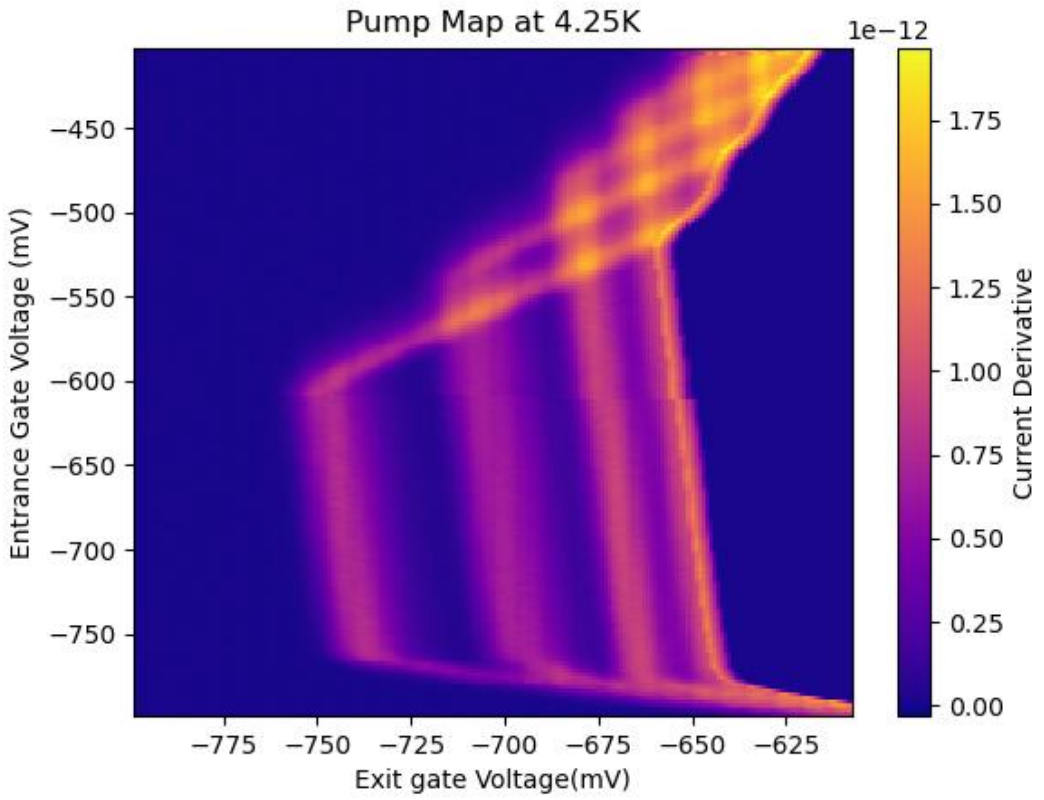




- We are operating in a pump regime where we a step the exit gate and sweep the channel gate

- Gap between the emission lines
    - Etiher LO phons ~36 meV (*Taubert et al [3])*
    - Other phonon emission branches

- How do we relate the extra emission lines? Must be something other than phonon emission occurring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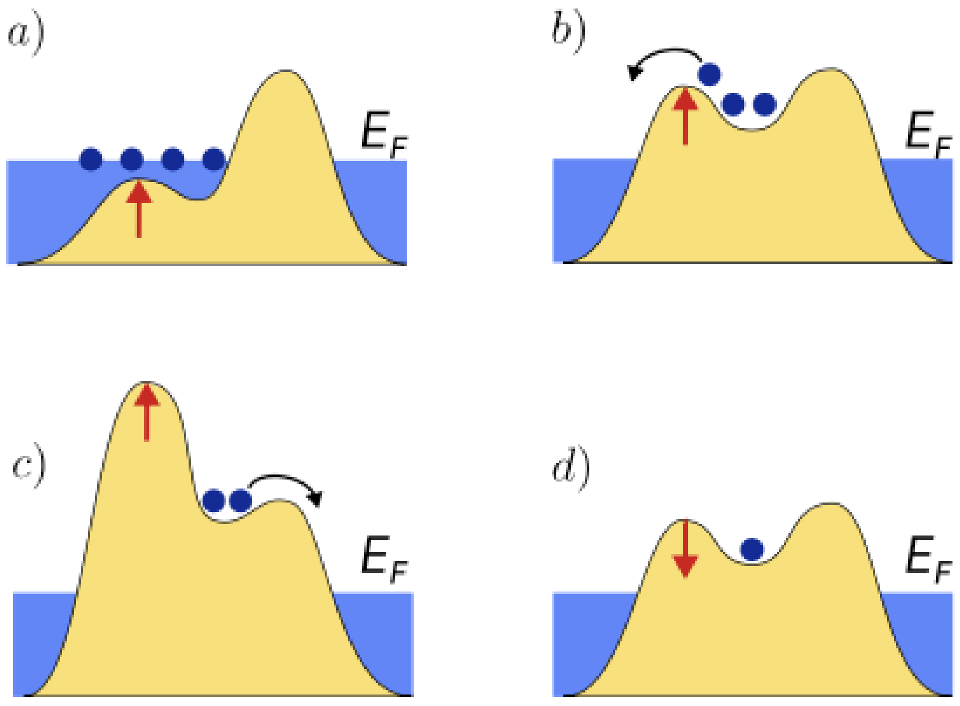

a)
E_F
b)
E_F
c)
E_F
d)
E_F

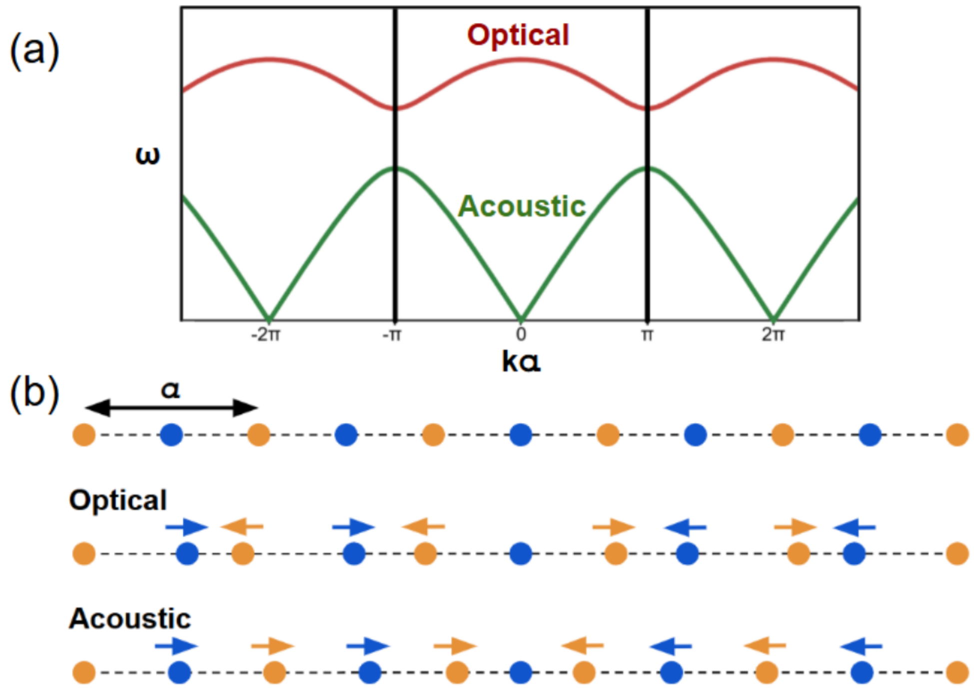
Phonon emission and electron de-excitation

- As electrons leave the pump they travel through the channels on the other side. Inherently as they travel these electrons lose energy.

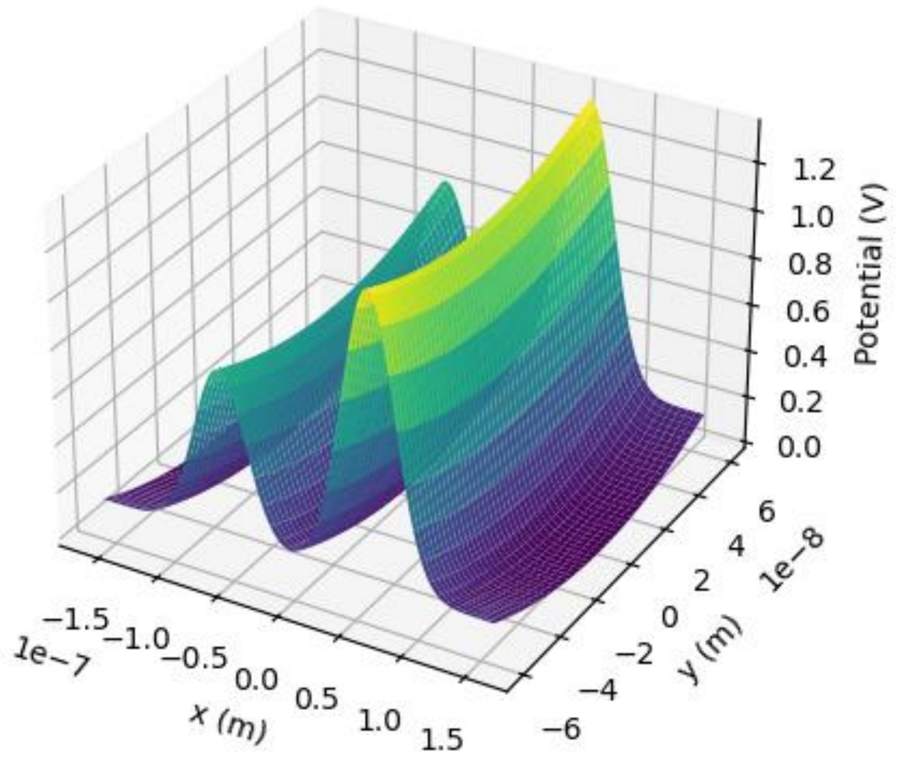
- This can occur through lattice scattering within the heterostructure. When this lattice scattering occurs often what occurs is the emission of a phonon

- Two different phonon branches
-
    - Optical phonons. Which displace unlike atoms in opposite directions
    - Acoustic phonons. Which displace unlike atoms in the same directions

- Phonons are further divided into categories defined by whether is is aligned with the direction of motion of the wave or not



Modeling the gate potential and future work



- Traditional approaches include modeling the gate potentials fully. This is often an arduous task and quite computationally expensive

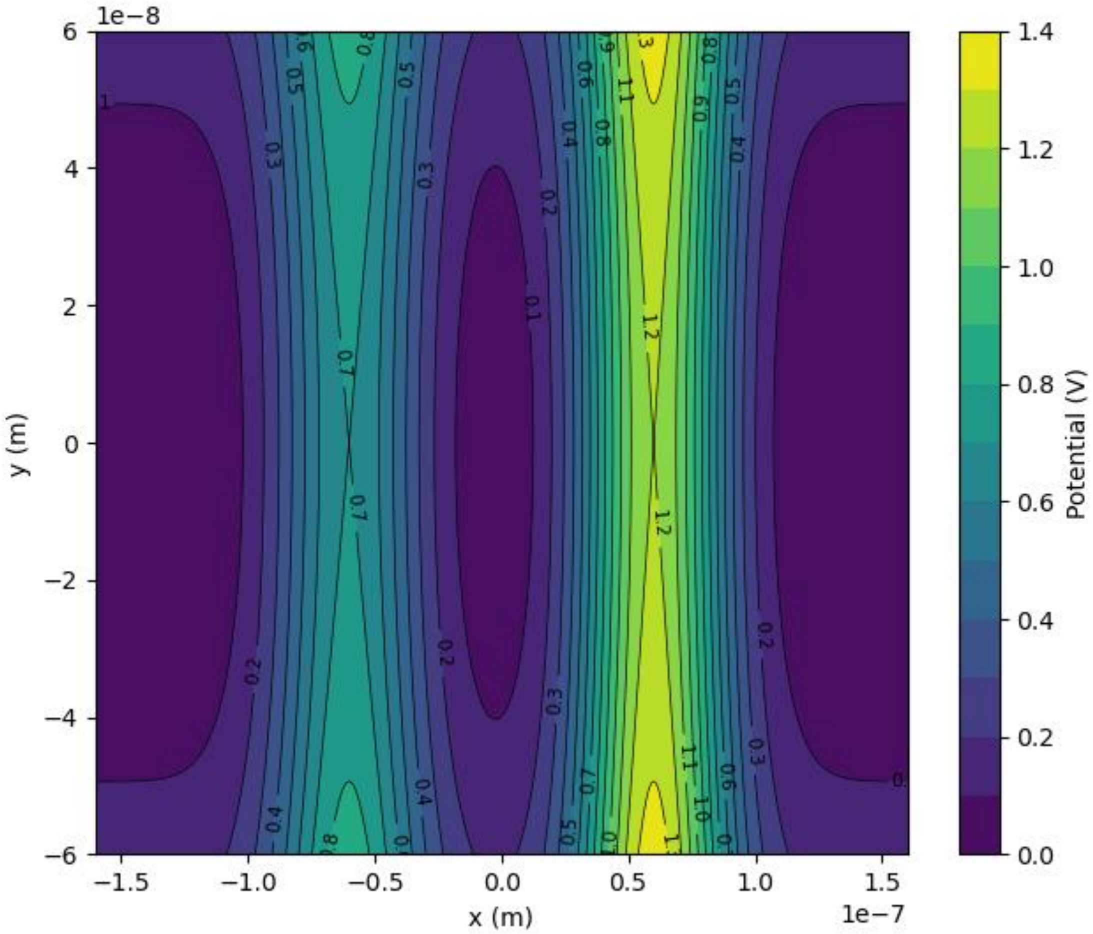
- This approach has shown promise in another paper by *Fletcher et al* [4]

- An approach which shows promise is to model the gates as a Gaussian barrier with a confining edge potential.

- We take the approach to model the energy of the electrons based on the charging energy of the dot whether it contains one or two electrons. (Do we know which is first?)

How do we go about this?

- Investigate the confining potential of the dot through following a few steps
    - Firstly defining the dot size and shape
    - Then working out for given gate voltages and dot sizes how many electrons are within the dot.
- We calculate the number of electrons in the dot through calculating the charging energy. Additionally taking into account the coulomb interaction between the electrons in the dot.
- Then use WKB to determine tunneling probability through the exit barrier
- Relate the tunneling probability to the measured current using the UDC model



References

[1] Kashcheyevs, Vyacheslavs, and Bernd Kaestner. ‘Universal Decay Cascade Model for Dynamic Quantum Dot Initialization’. *Physical Review Letters* 104, no. 18 (2010): 186805. https://doi.org/10.1103/PhysRevLett.104.186805.

[2] Fletcher, J. D., P. See, H. Howe, et al. ‘Clock-Controlled Emission of Single-Electron Wave Packets in a Solid-State Circuit’. *Physical Review Letters* 111, no. 21 (2013): 216807. https://doi.org/10.1103/PhysRevLett.111.216807.

[3] Taubert, D., C. Tomaras, G. J. Schinner, et al. ‘Relaxation of Hot Electrons in a Degenerate Two-Dimensional Electron System: Transition to One-Dimensional Scattering’. *Physical Review B* 83, no. 23 (2011): 235404. https://doi.org/10.1103/PhysRevB.83.235404.

[4] Fletcher, J. D., M. Kataoka, S. P. Giblin, et al. ‘Stabilization of Single-Electron Pumps by High Magnetic Fields’. *Physical Review B* 86, no. 15 (2012): 155311. https://doi.org/10.1103/PhysRevB.86.155311.