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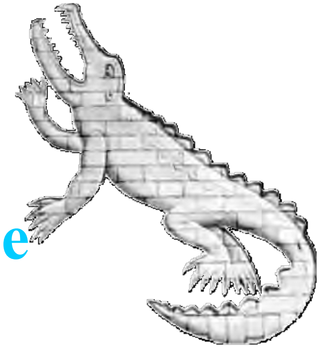

Single-Electron Quantum Dots moving in Surface-Acoustic-Wave Minima:

Electron “Ping-Pong”, and Quantum Coherence, and conversion to photons

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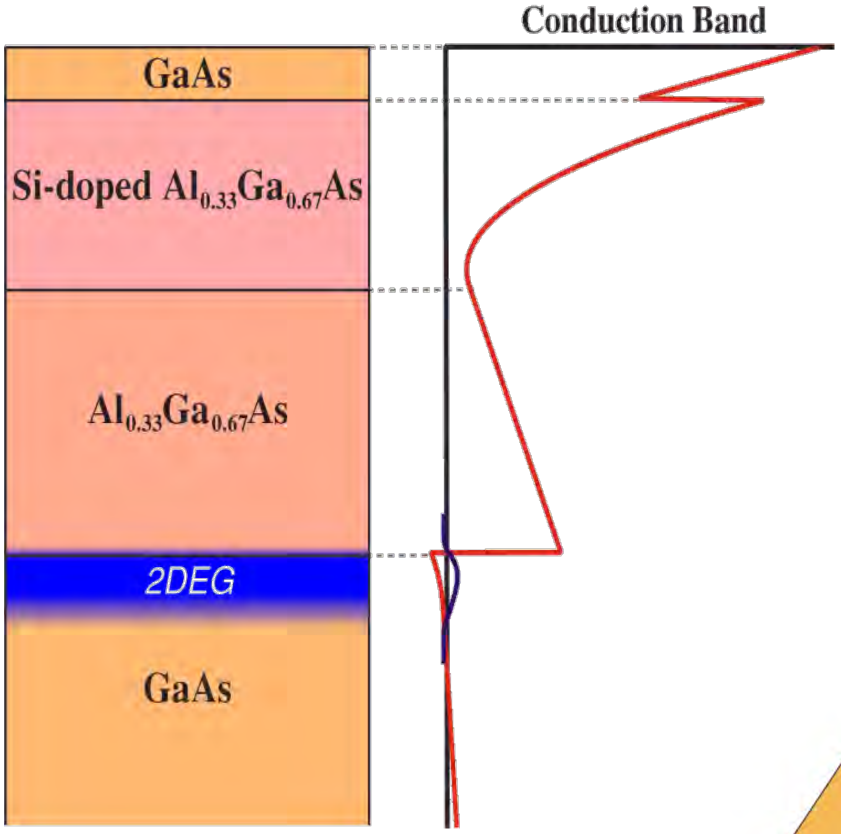
EPSRC Engineering and Physical Sciences Research Council

NPL National Physical Laboratory

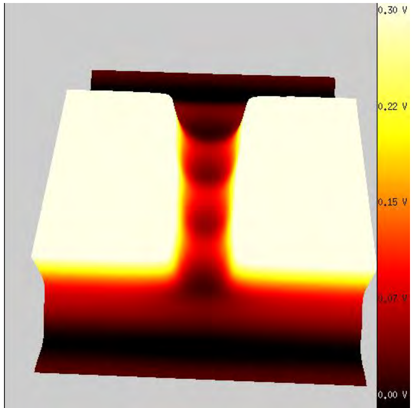
Outline

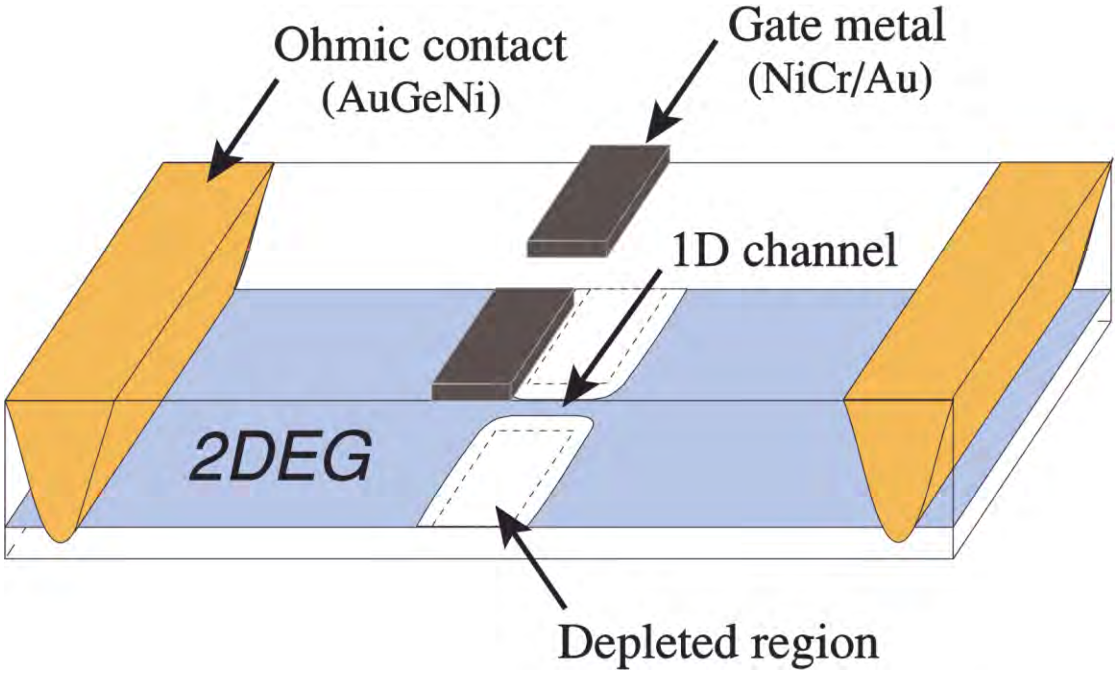
- Dynamic single-electron quantum dots driven by a surface acoustic wave (SAW)
  - current standard
  - single-photon source
  - spin readout by polarised photon emission
  - transfer of single charges
- Transfer of an electron between static dots
  - single-electron “ping pong”
- Quantum oscillations in a single SAW dot
  - initialisation and detection in same place
  - initialisation and detection in separate places
- Emission of photons from p-n junction
- Conclusions

GaAs-AlGaAs heterostructures and gates



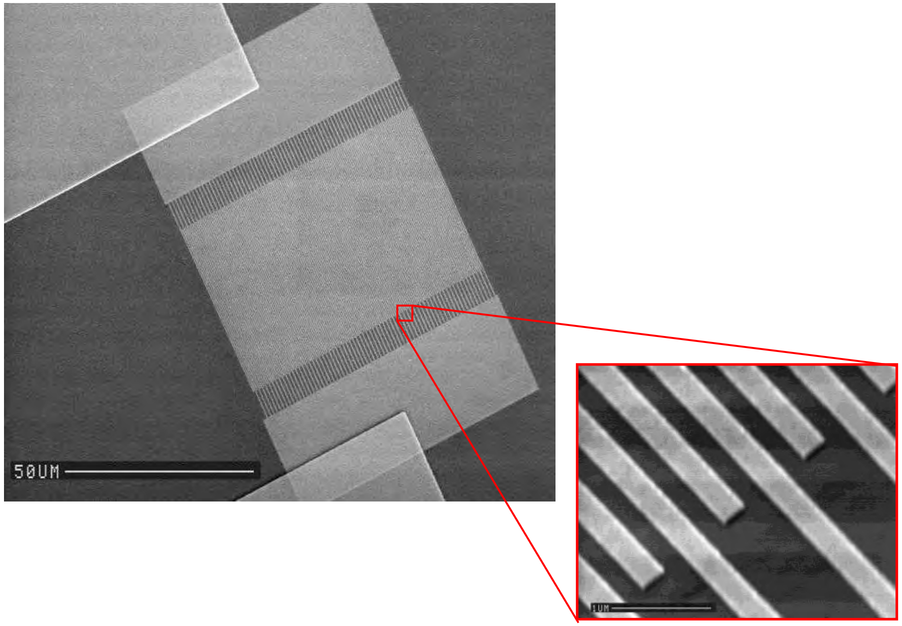
- Band offset → 2D potential well
- Doping offset from well
  - very little scattering
  - 2D electron gas (2DEG)
- Gates on surface deplete 2DEG
  - narrow channel between split gates
  - very flexible technique

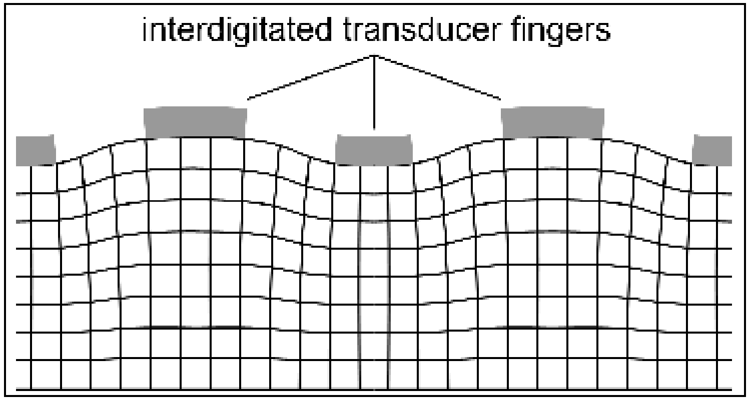




Surface acoustic waves (SAWs)

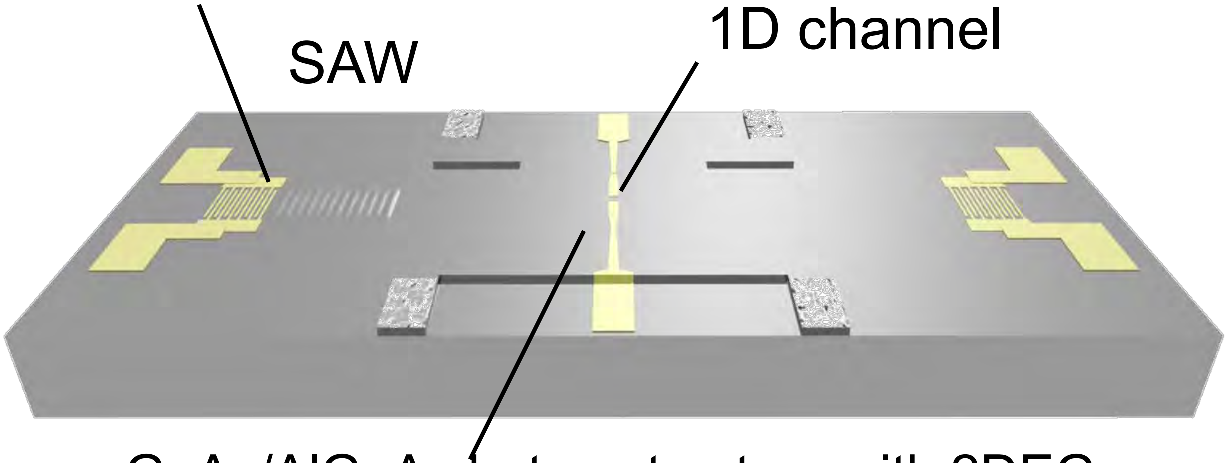
- Rayleigh waves generated on a piezoelectric material by applying a radio-frequency signal to a transducer at its resonant frequency





- In a piezoelectric material the strain wave is accompanied by an electric field

SAW single-electron transport

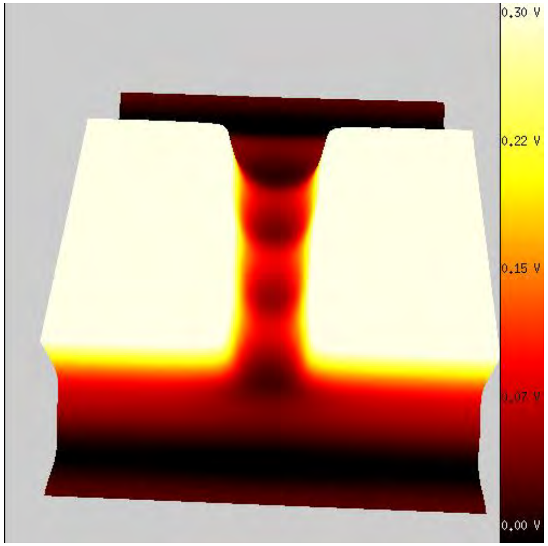


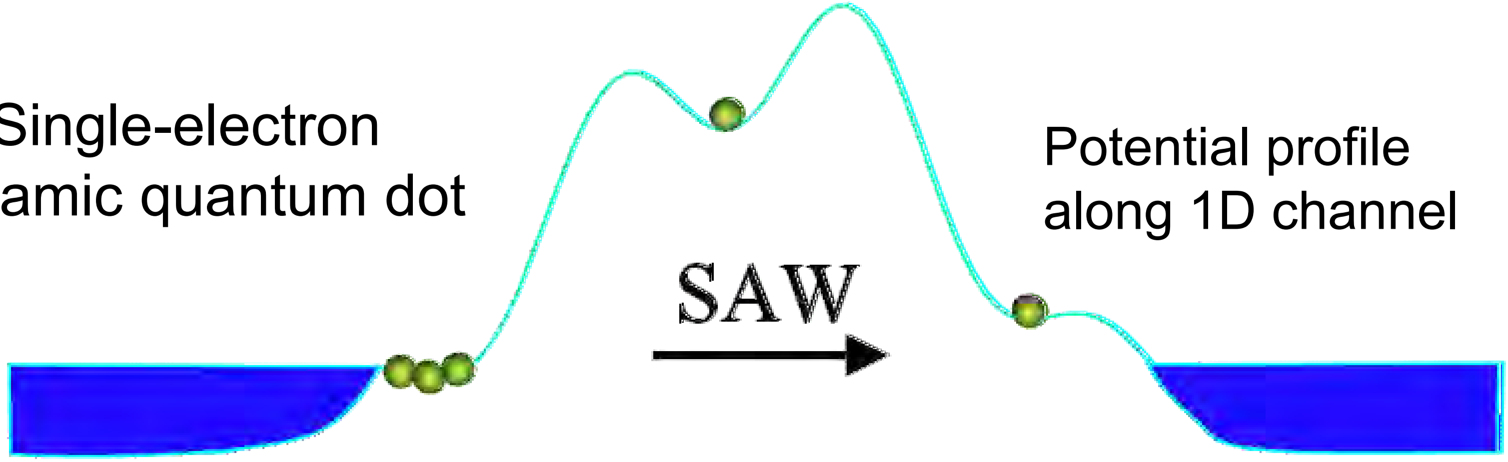
Transducer

SAW

1D channel

GaAs/AlGaAs heterostructure with 2DEG



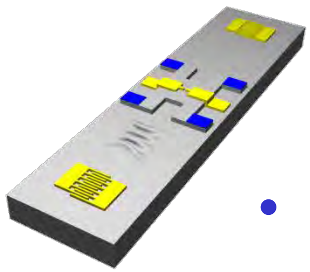


Single-electron
dynamic quantum dot

E_F

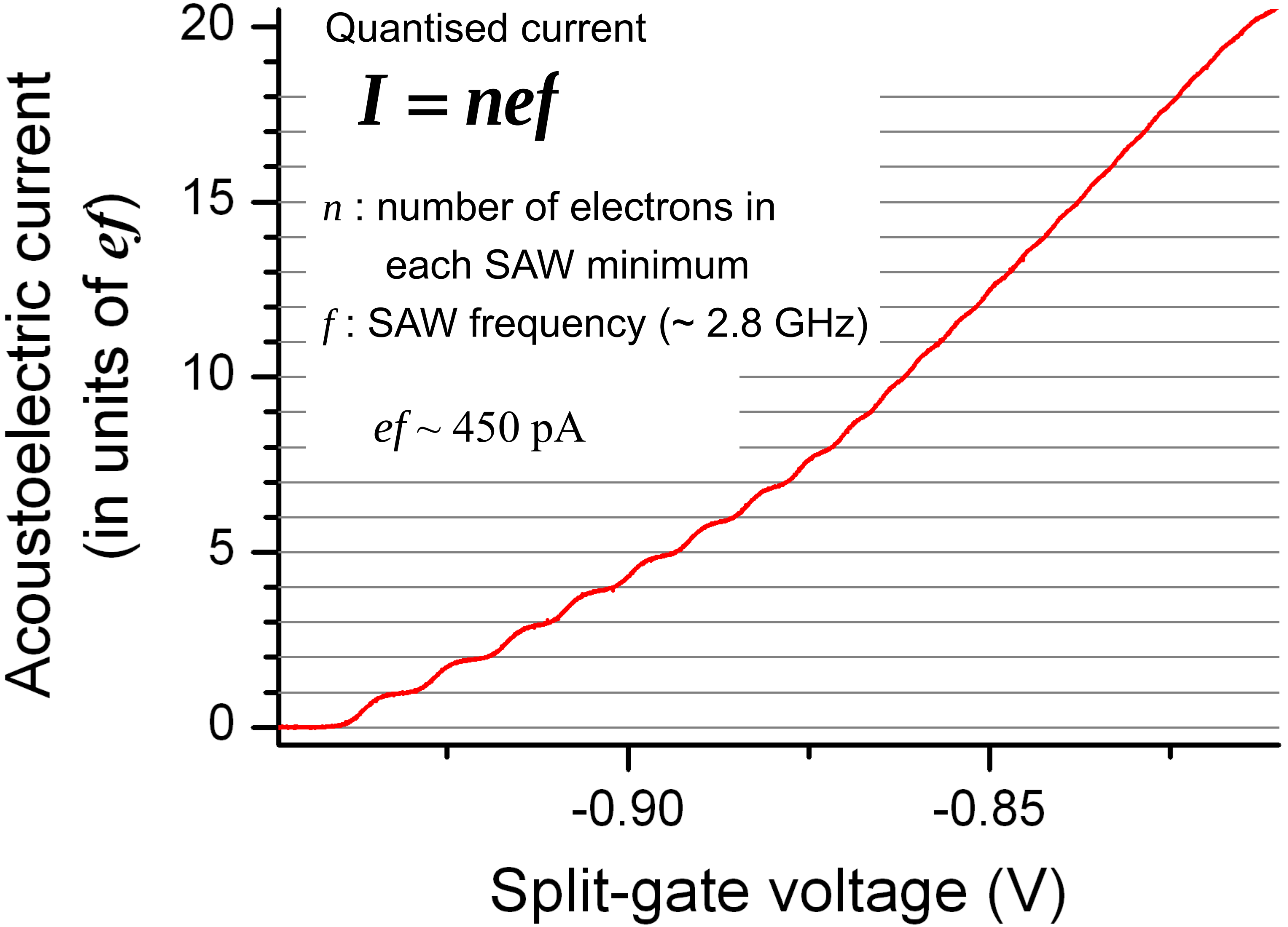
SAW

Potential profile
along 1D channel



Why dynamic quantum dots?

- SAW current quantisation



Quantised current

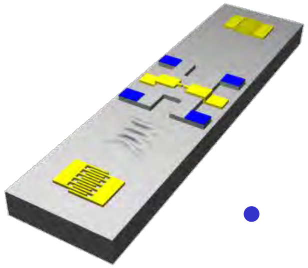
$$I = nef$$

n : number of electrons in each SAW minimum

f : SAW frequency (~ 2.8 GHz)

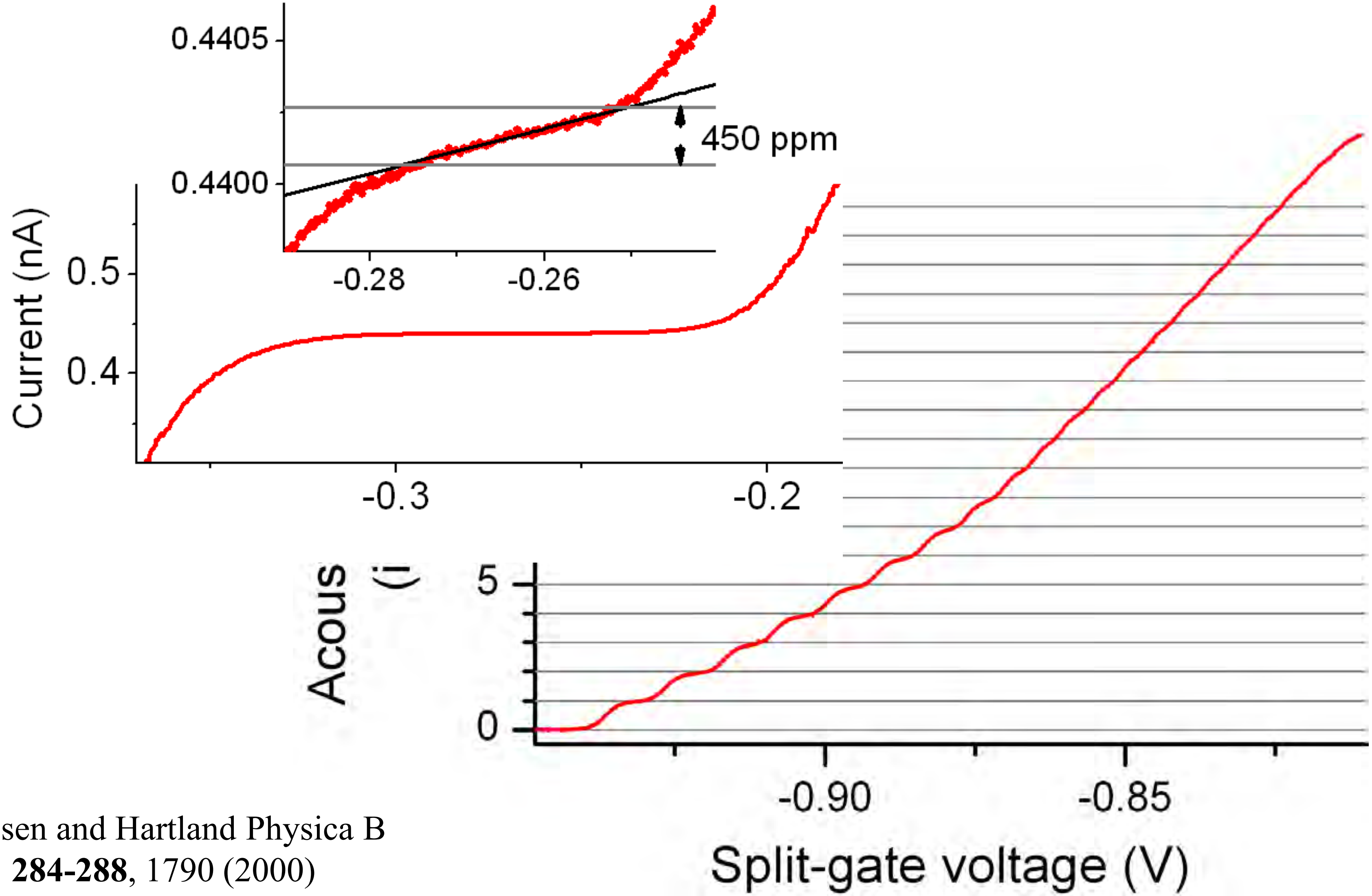
$ef \sim 450$ pA

Shilton *et al.*, J. Phys.: Condens. Matter **8**, L531 (1996)

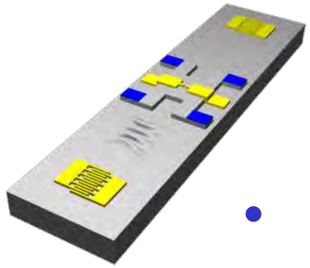


Why dynamic quantum dots?

- Metrology: current standard

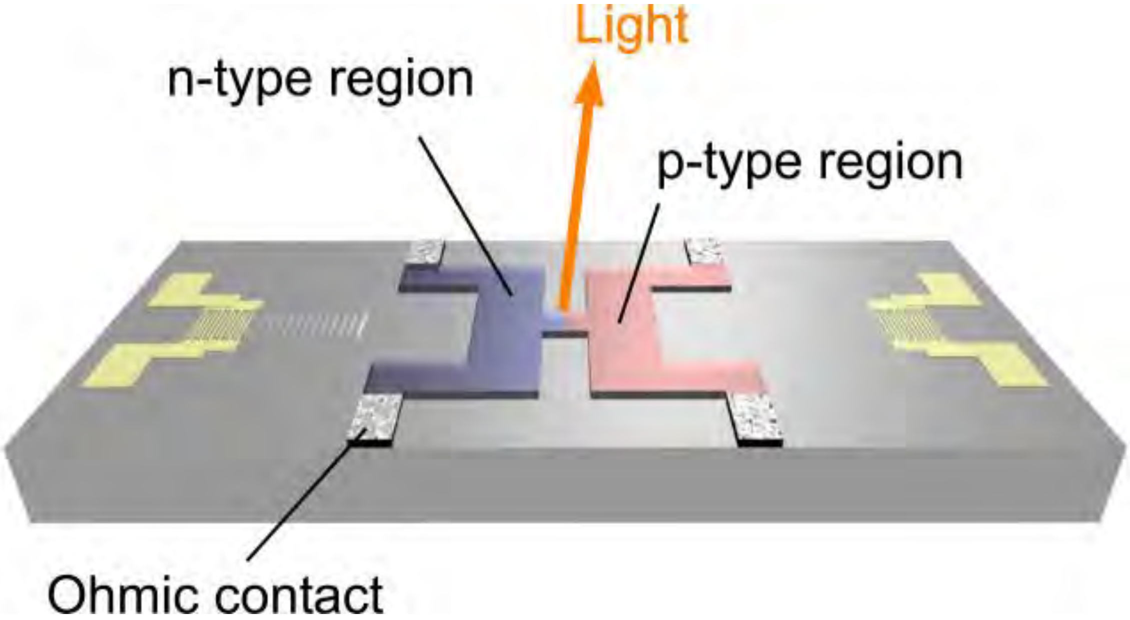


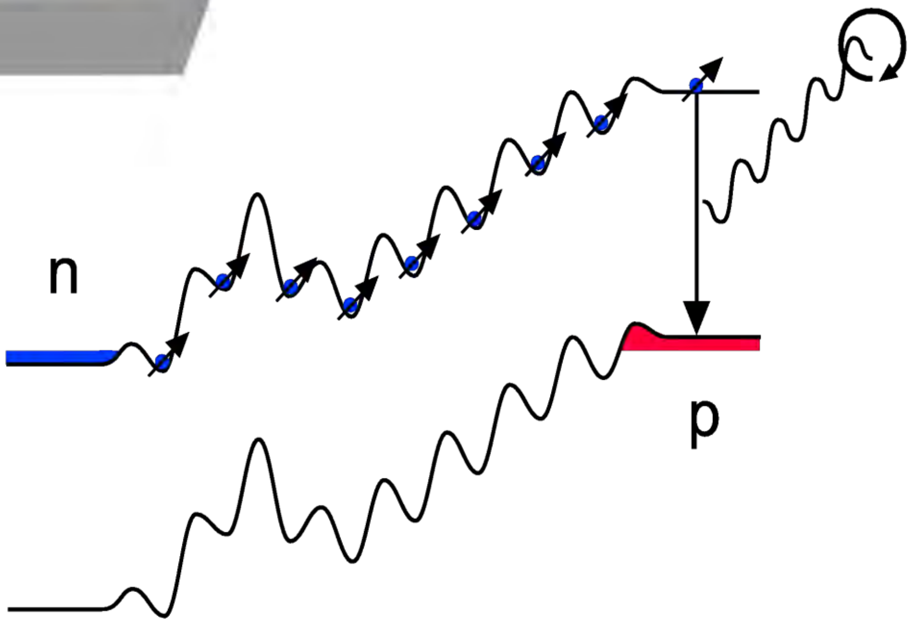
Janssen and Hartland Physica B **284-288**, 1790 (2000)



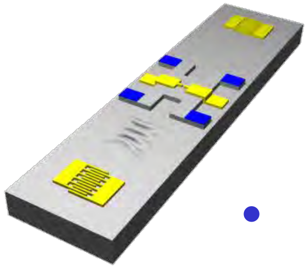
Why dynamic quantum dots?

- Quantum cryptography: single-photon source



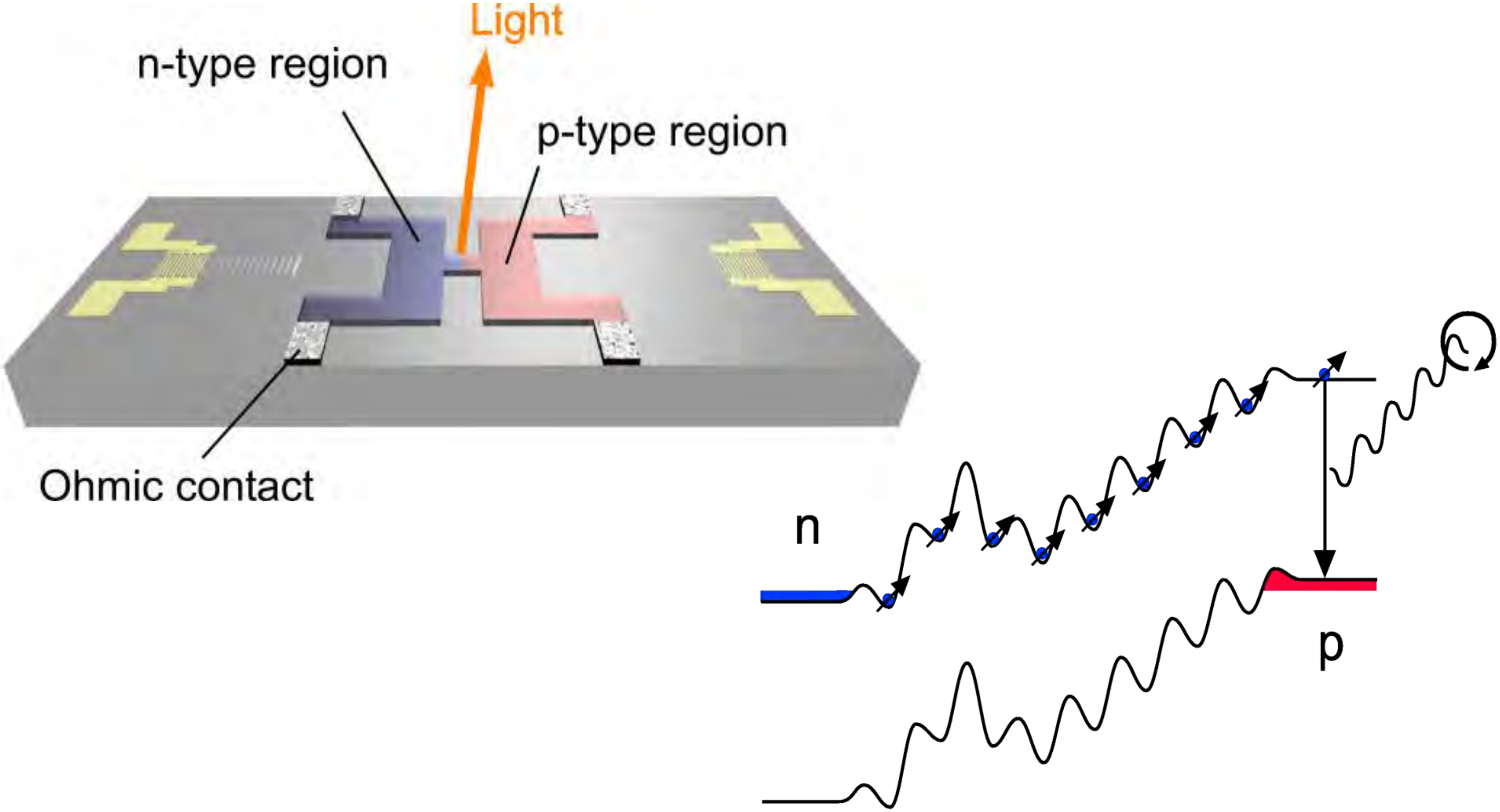


Foden *et al.*, PRA **62**, 011803 (2000), Gell *et al.*, Appl. Phys. Lett., 91, 013506 (2007)

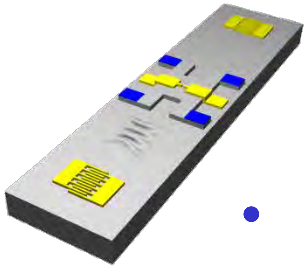


Why dynamic quantum dots?

- Quantum cryptography: single-photon source
- Spin readout *via* polarised photons

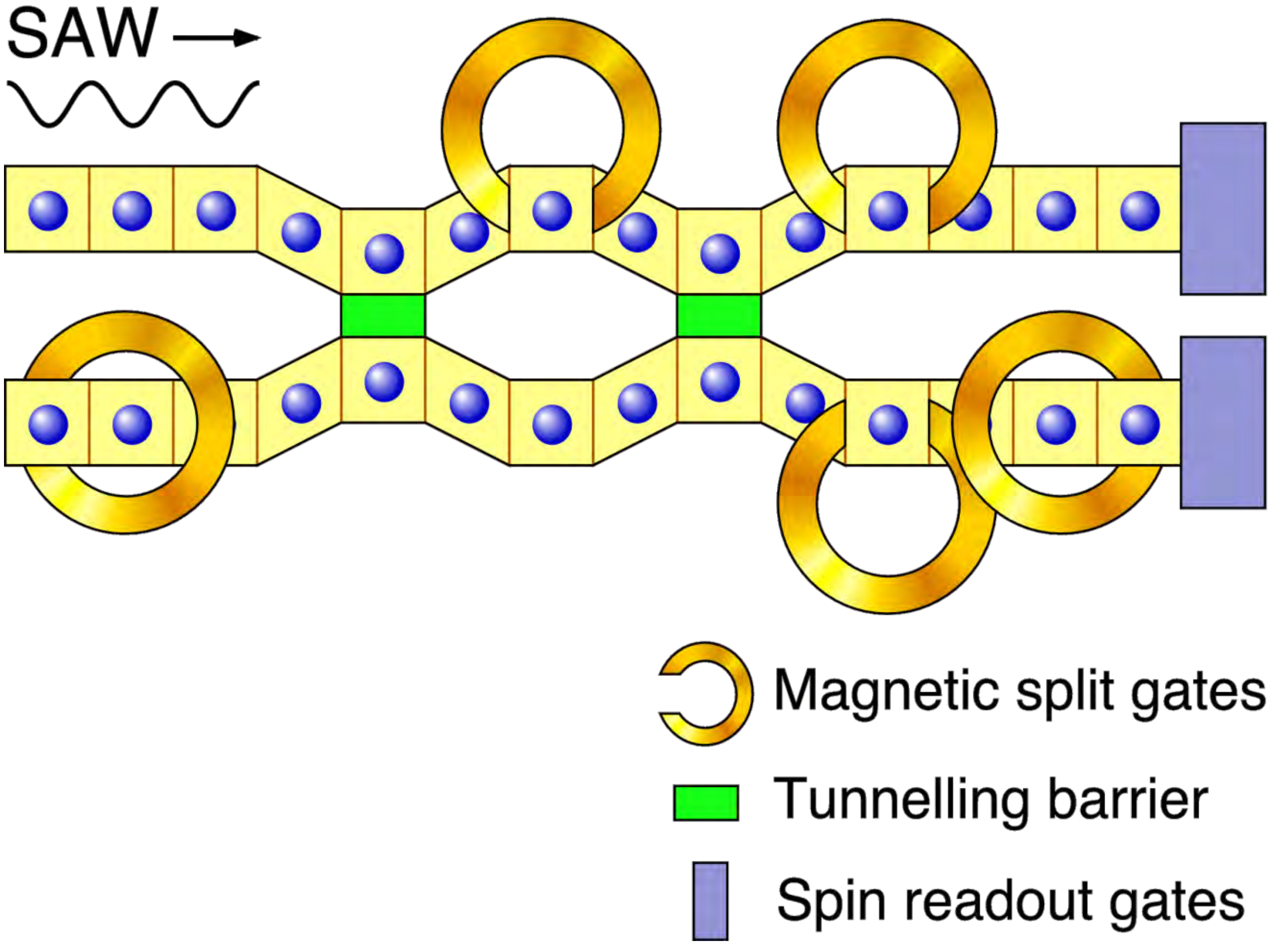


Foden *et al.*, *Phys. Rev. A* **62**, 011803 (2000), Gell *et al.*, *Appl. Phys. Lett.*, **91**, 013506 (2007)



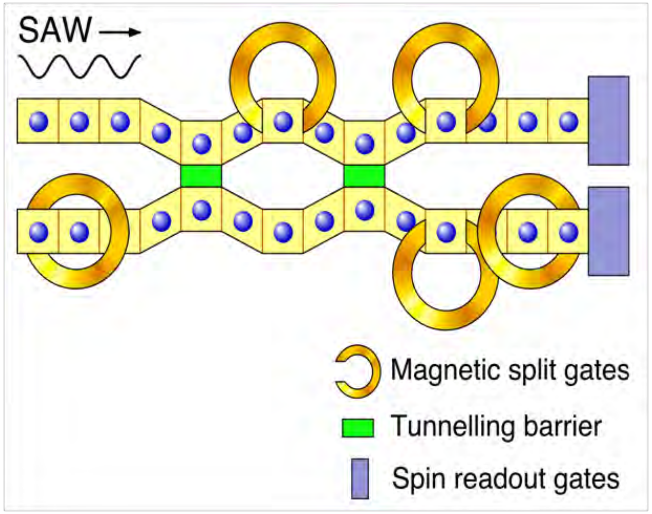
Why dynamic quantum dots?

- Quantum computation

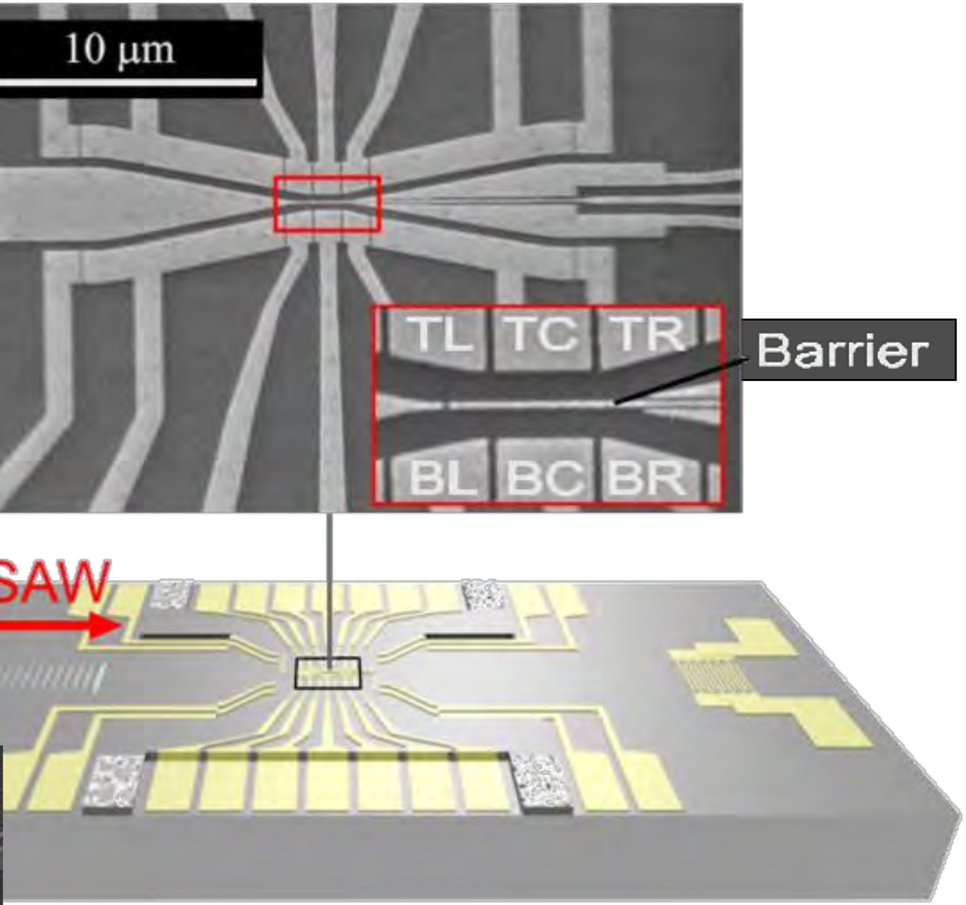


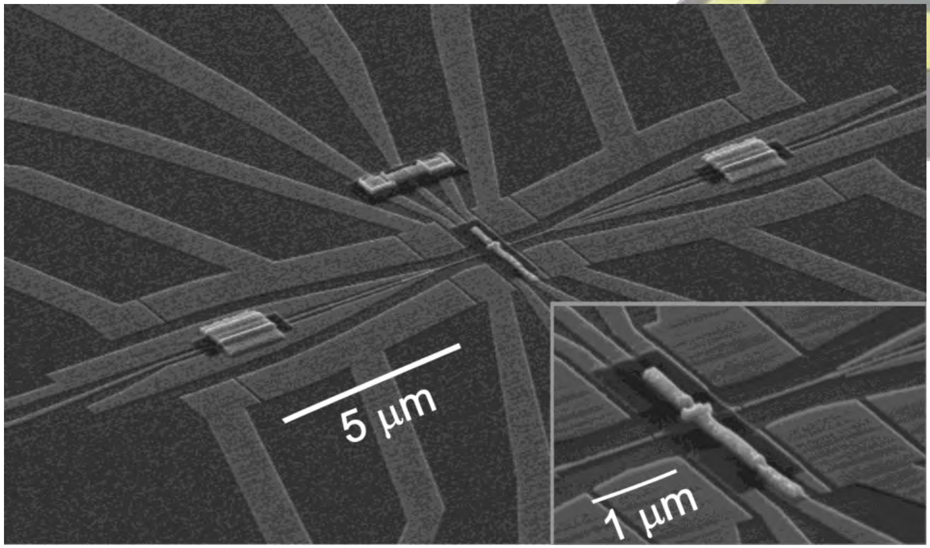
Barnes *et al.*, *Phys. Rev. B* **62**, 8410 (2000)

The SAW quantum computing project



Barnes *et. al.* PRB **62** 8410 (2000)

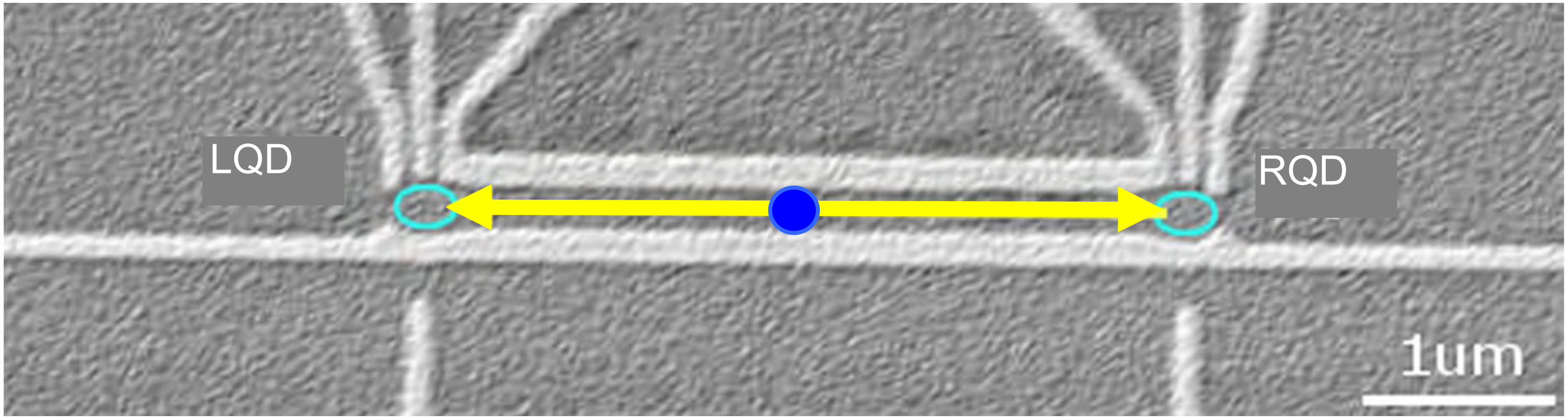




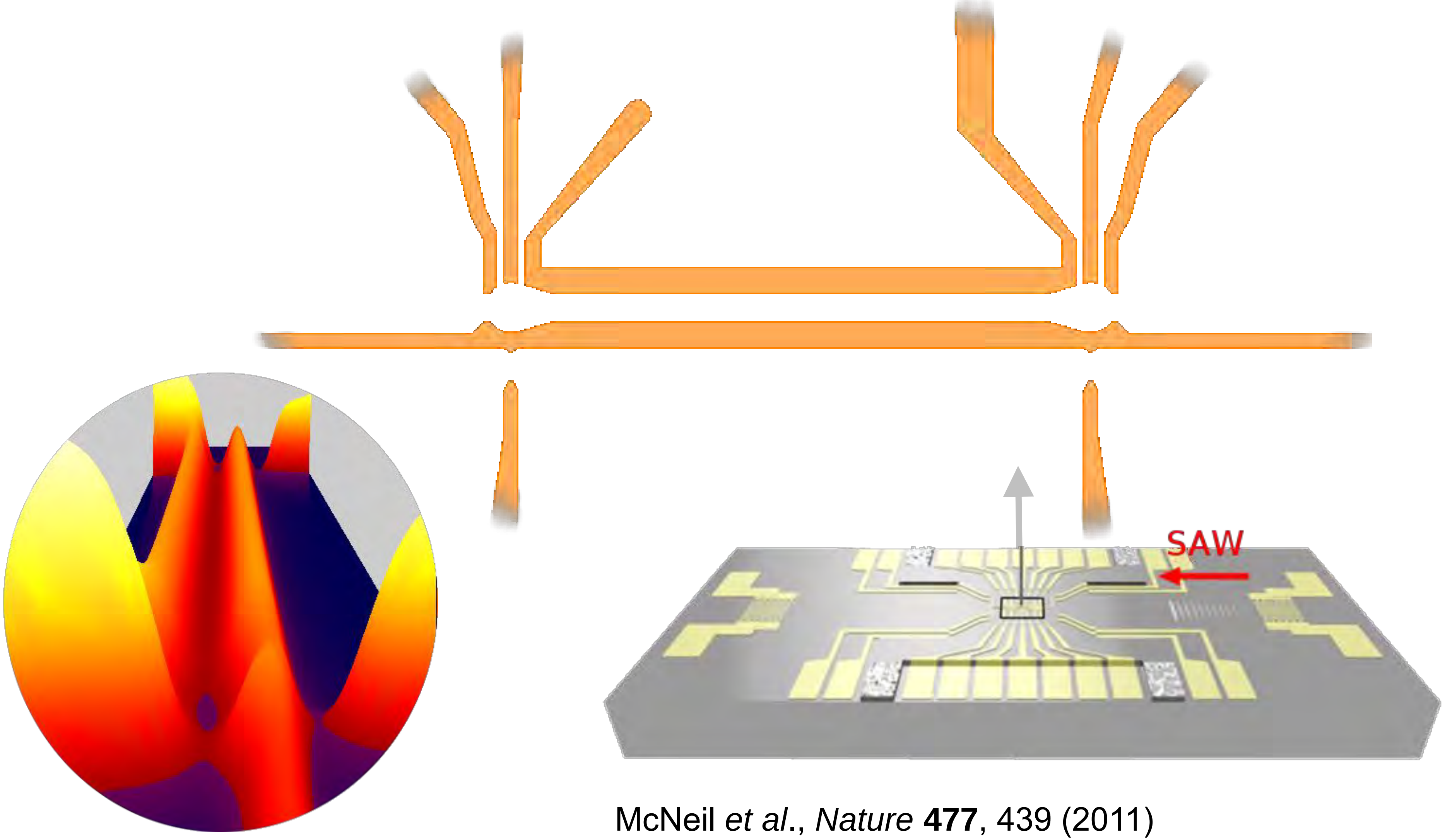
- Use many surface gates to control channels in each region

Transfer of quantum information

- A quantum computer will need to be able to move qubits to entangle adjacent ones, or to store and retrieve qubits
  - quantum repeater for cryptography?
- Transfer spin qubits from static dots to "flying" qubits
  - e.g. SAW-driven qubits, photon qubits
  - convert back once reach memory
- We have designed devices to transfer single electrons over long distances (4 μm) back and forth between static dots
  - can play with a given electron for e.g. 10 minutes
  - spin transport and coherence still remain to be demonstrated…



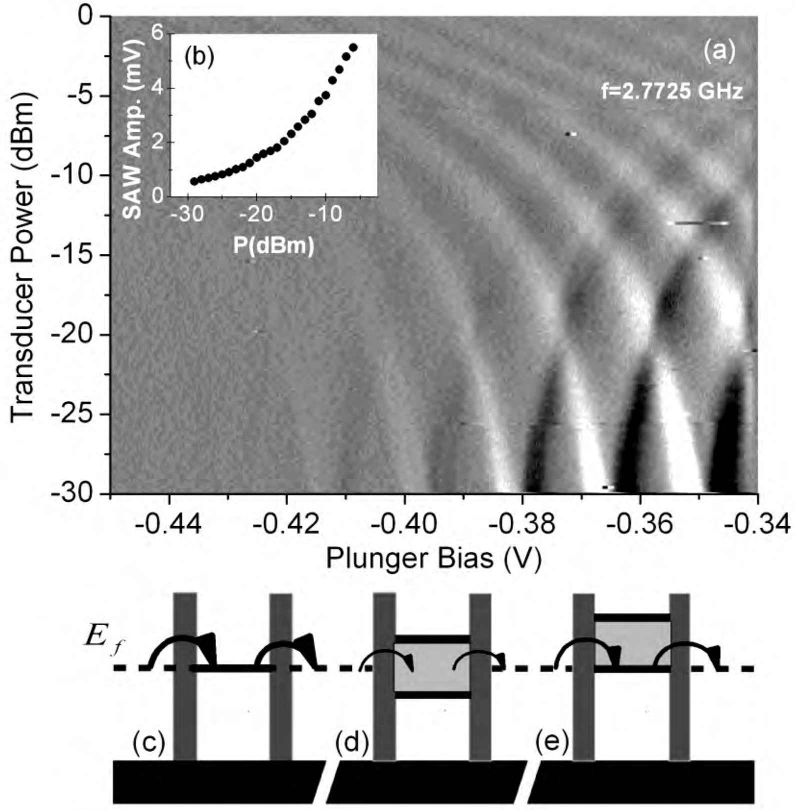
Single electron transfer between two QDs

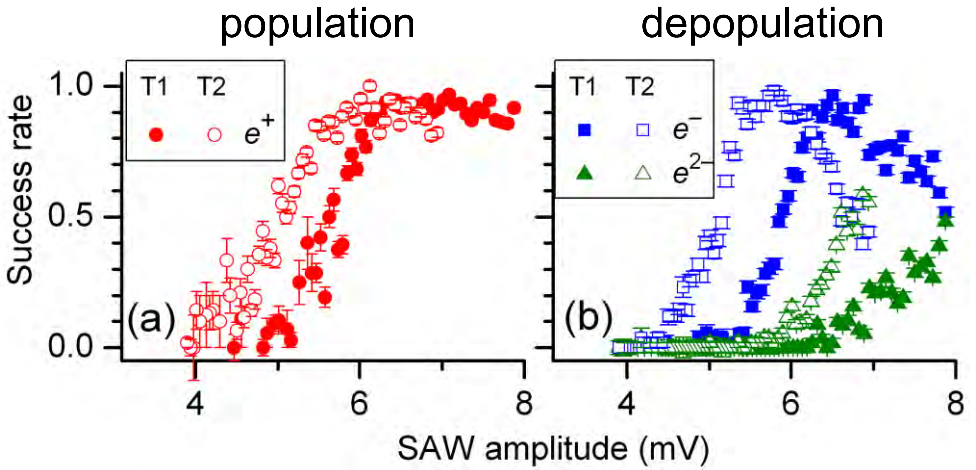


McNeil *et al.*, *Nature* **477**, 439 (2011)

SAW amplitude dependence

- SAW potential amplitude can be calibrated by measuring conductance peak splitting

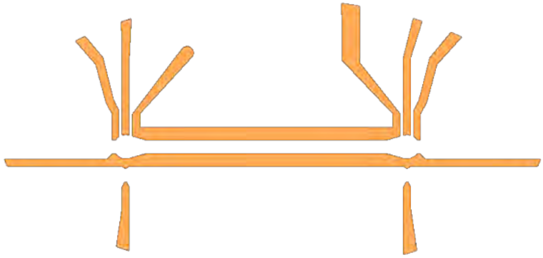




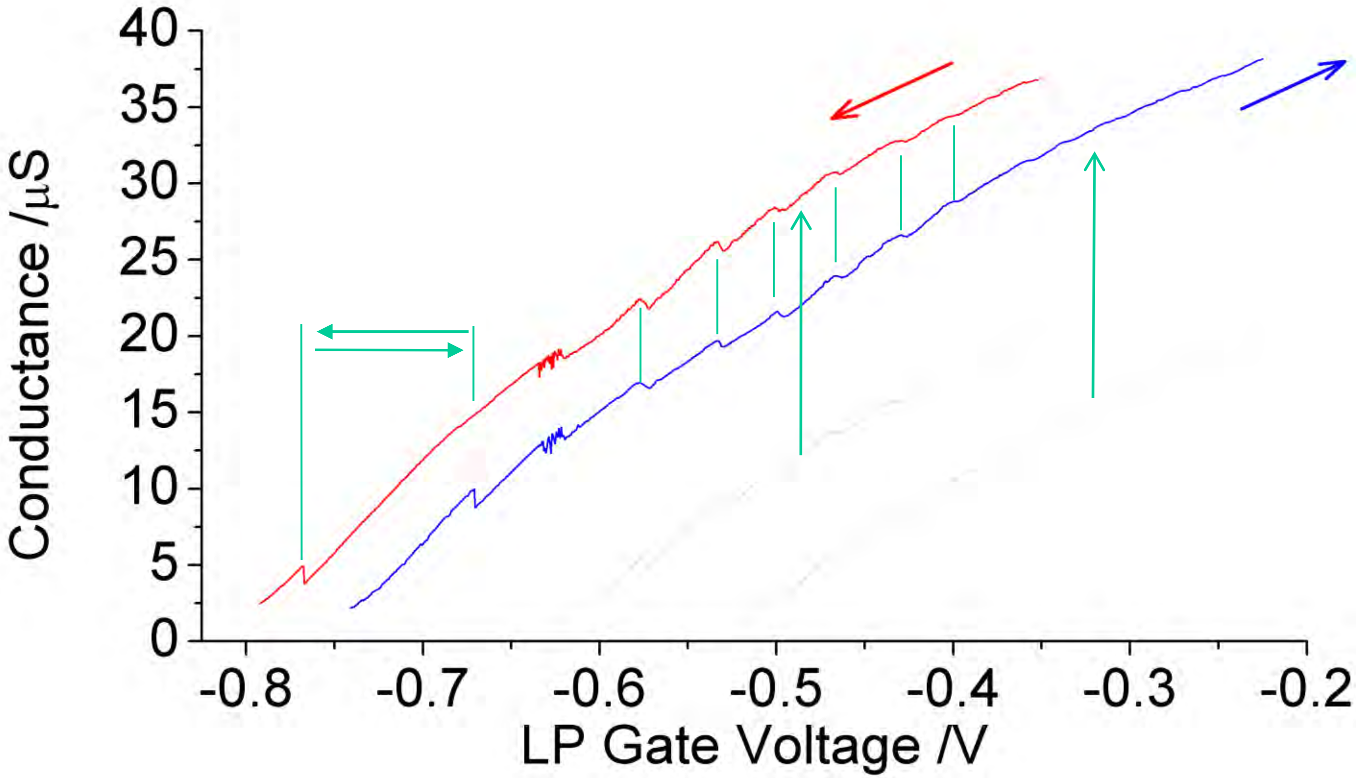
- Both transducers (T1, T2) give similar results within error
  ⇒ mechanism is lowering of a barrier
- Success rate ~ 1 when SAW amplitude large enough
- If amplitude too large, double depopulation (-2*e*) occurs

Schneble *et al.*, Appl. Phys. Lett. **89**, 122104 (2006)

Setting up a dot

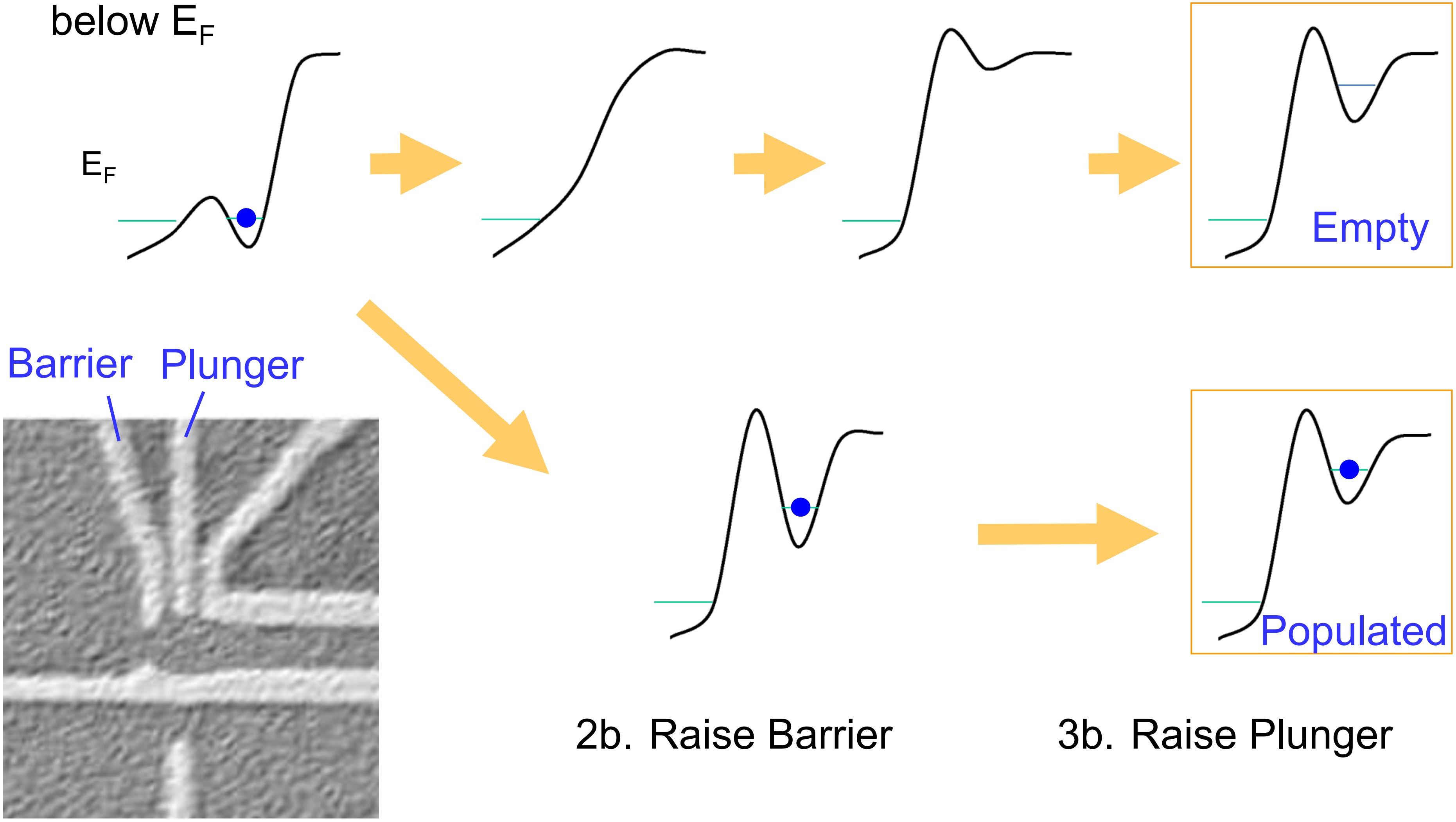


- Barriers pinched off
  - cannot measure conductance oscillations
  - use "**detector**", look for hysteresis in losing/gaining electron



  - moving from open to isolated dot, transitions become steeper and show hysteresis

Dot initialisation



1. Start with dot below E_F

2a. Raise Plunger

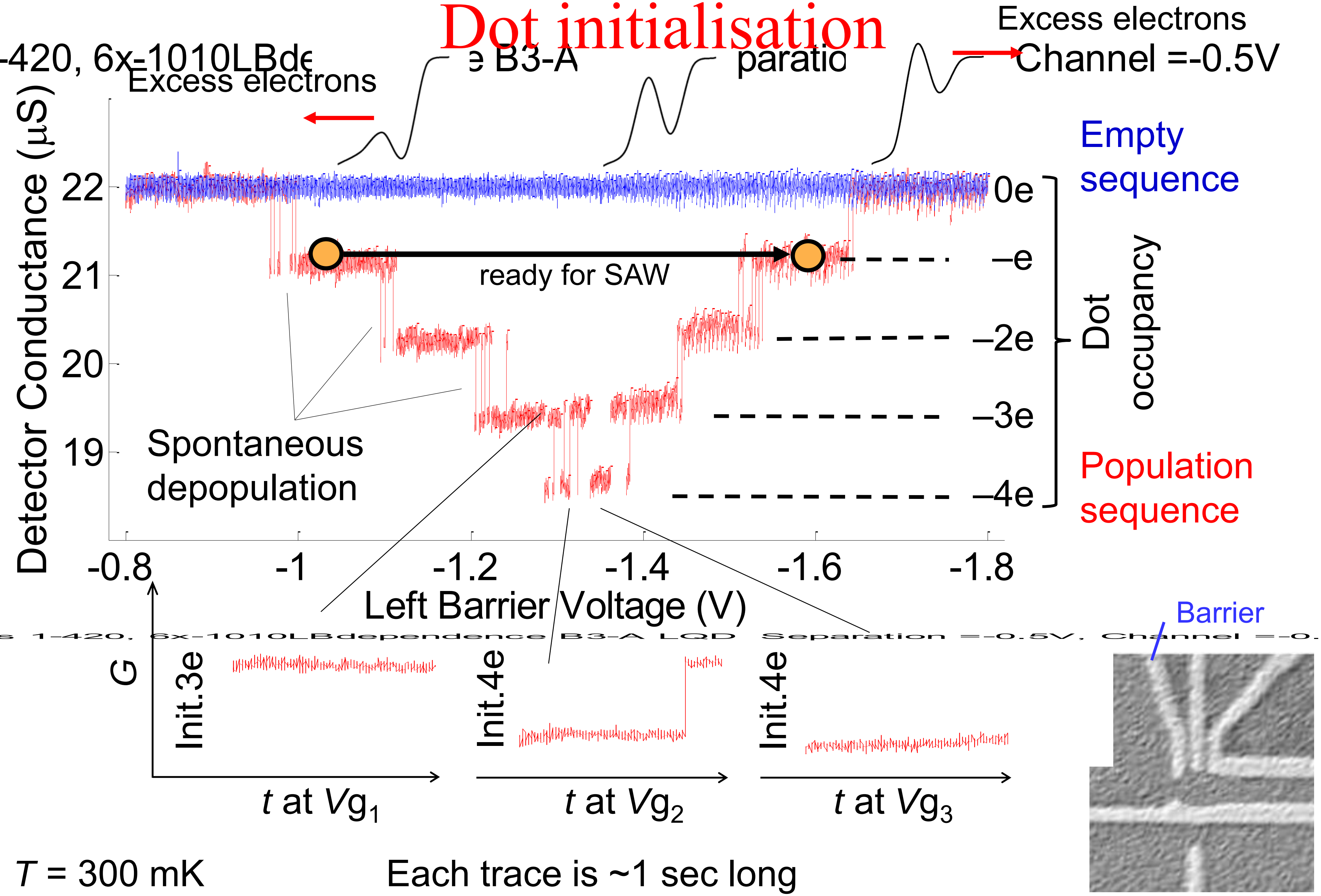
3a. Raise Barrier

4a. Lower Plunger

2b. Raise Barrier

3b. Raise Plunger

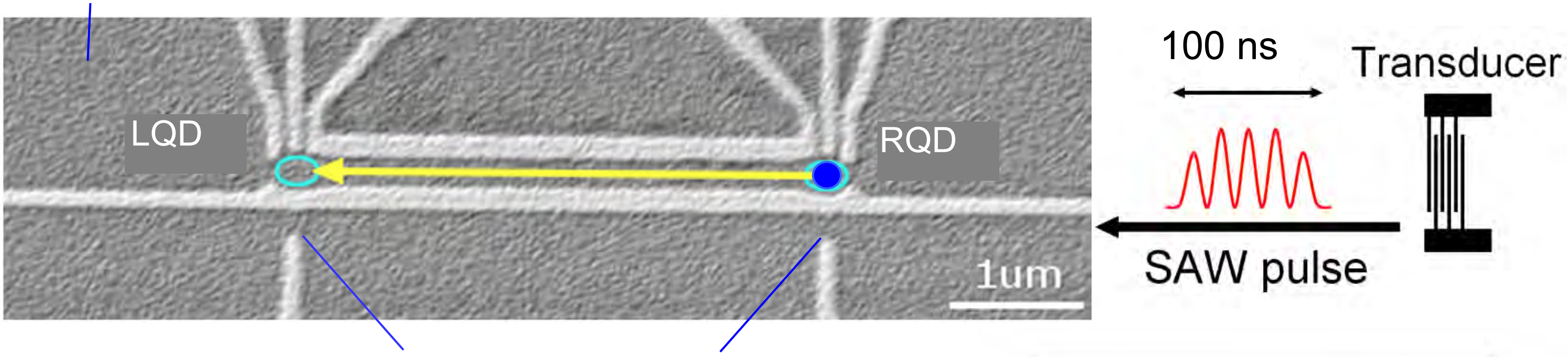
Dot initialisation

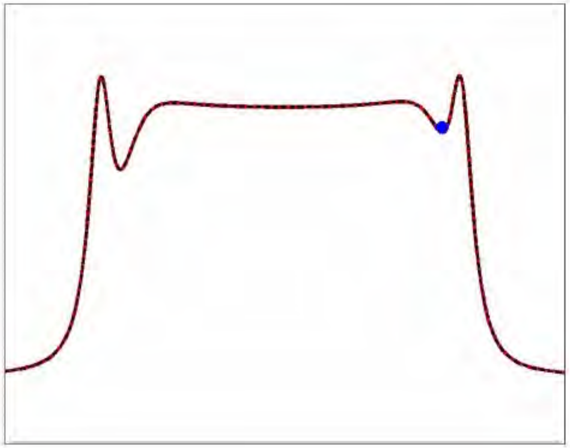


T = 300 mK

Each trace is ~1 sec long

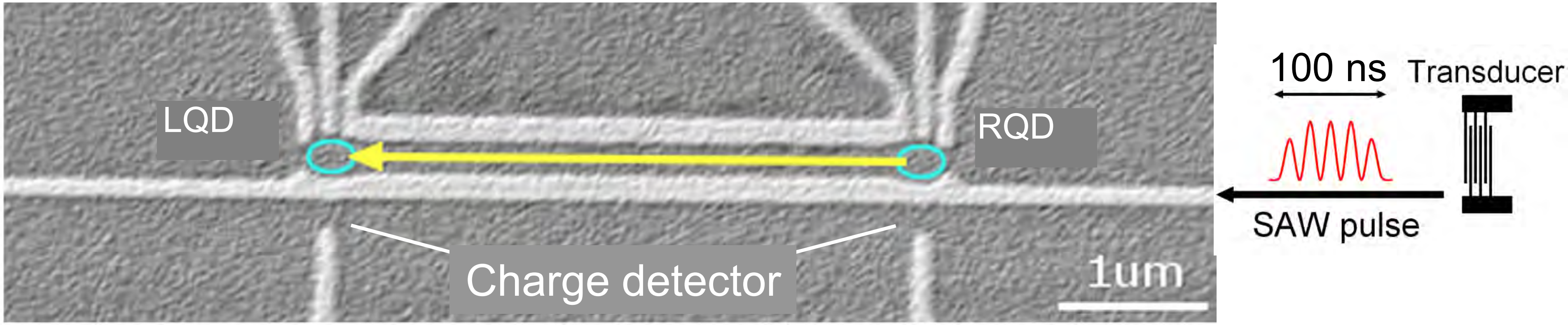
Pulse sequence

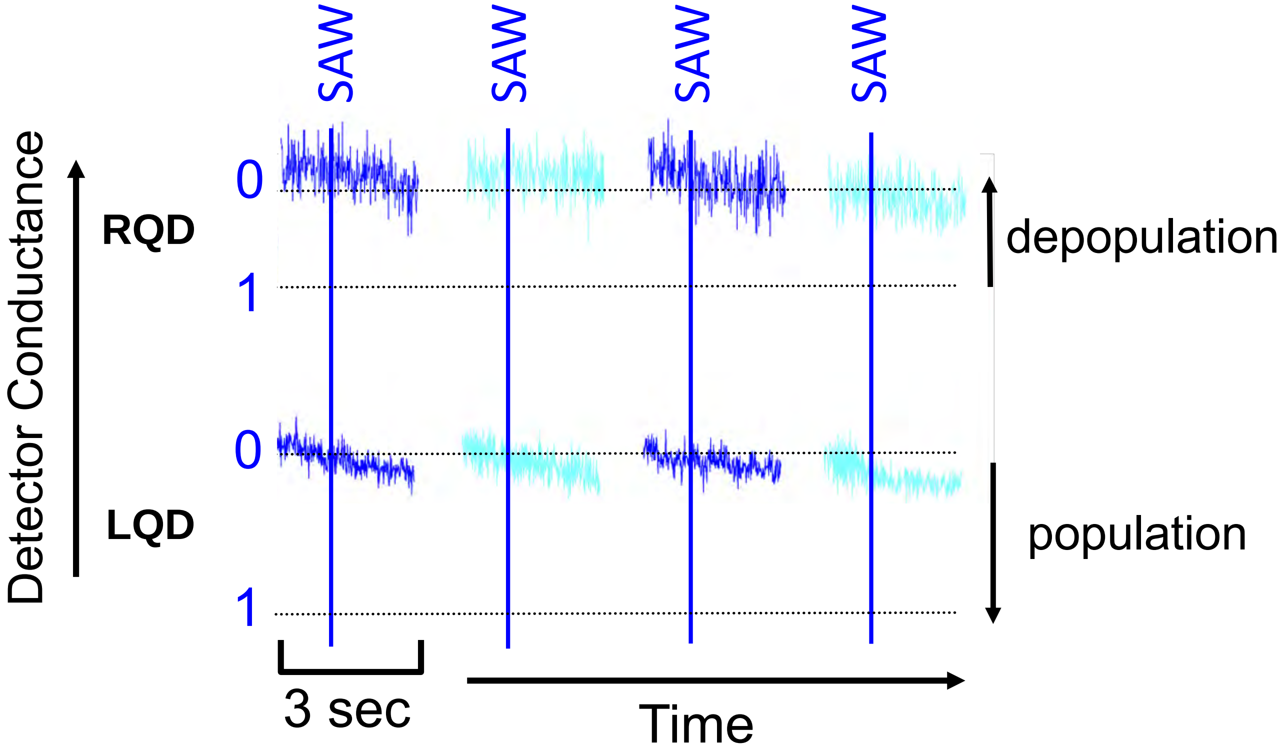




- Prepare channel
  - SAW pulse to clear channel
- Initialise dots
- Fire a SAW pulse (100 ns)
  - monitor **detectors** before and after
- Detect electron population/depopulation
  - electron disappears from one dot, reappears in the other

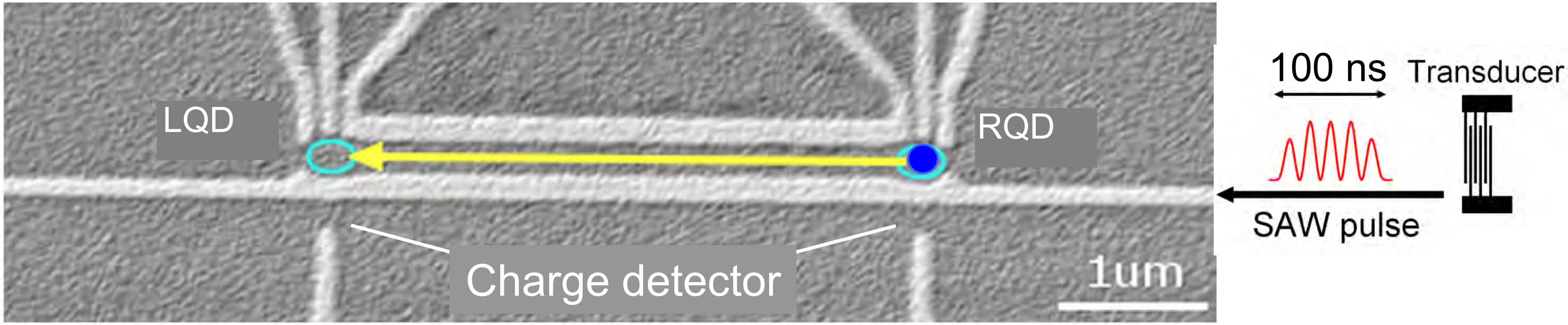
Single-electron transfer

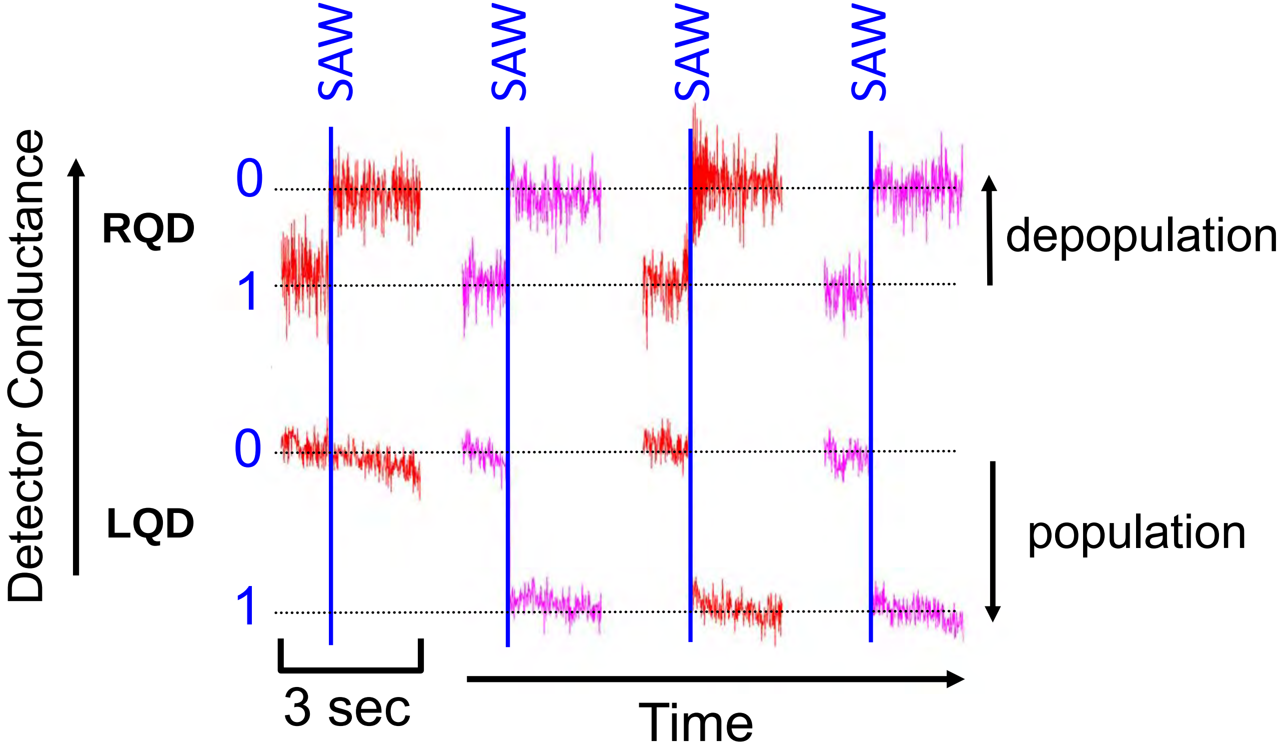




- RQD empty
- LQD empty
- Send SAW pulse
  - no electrons appear from channel after SAW pulse

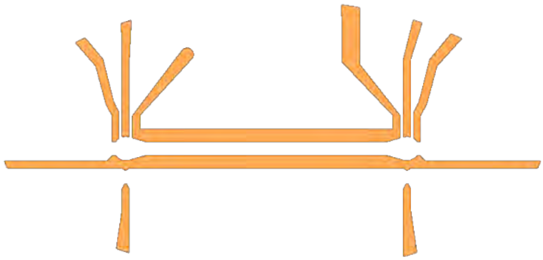
Single-electron transfer

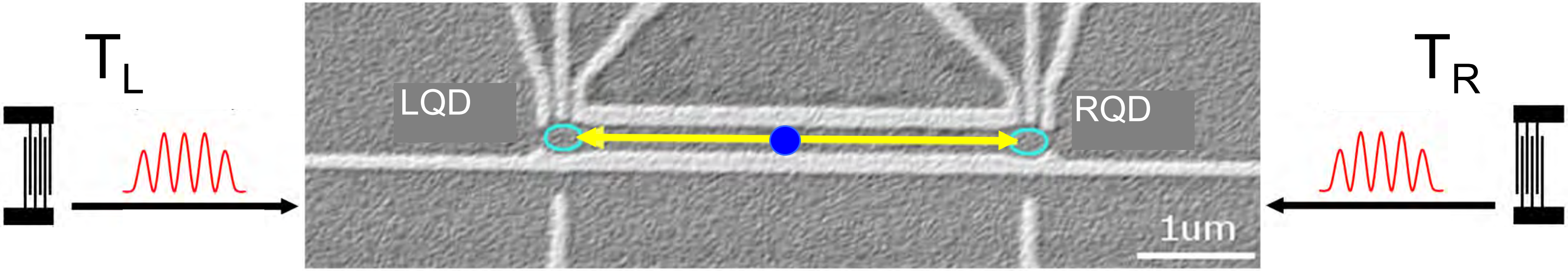


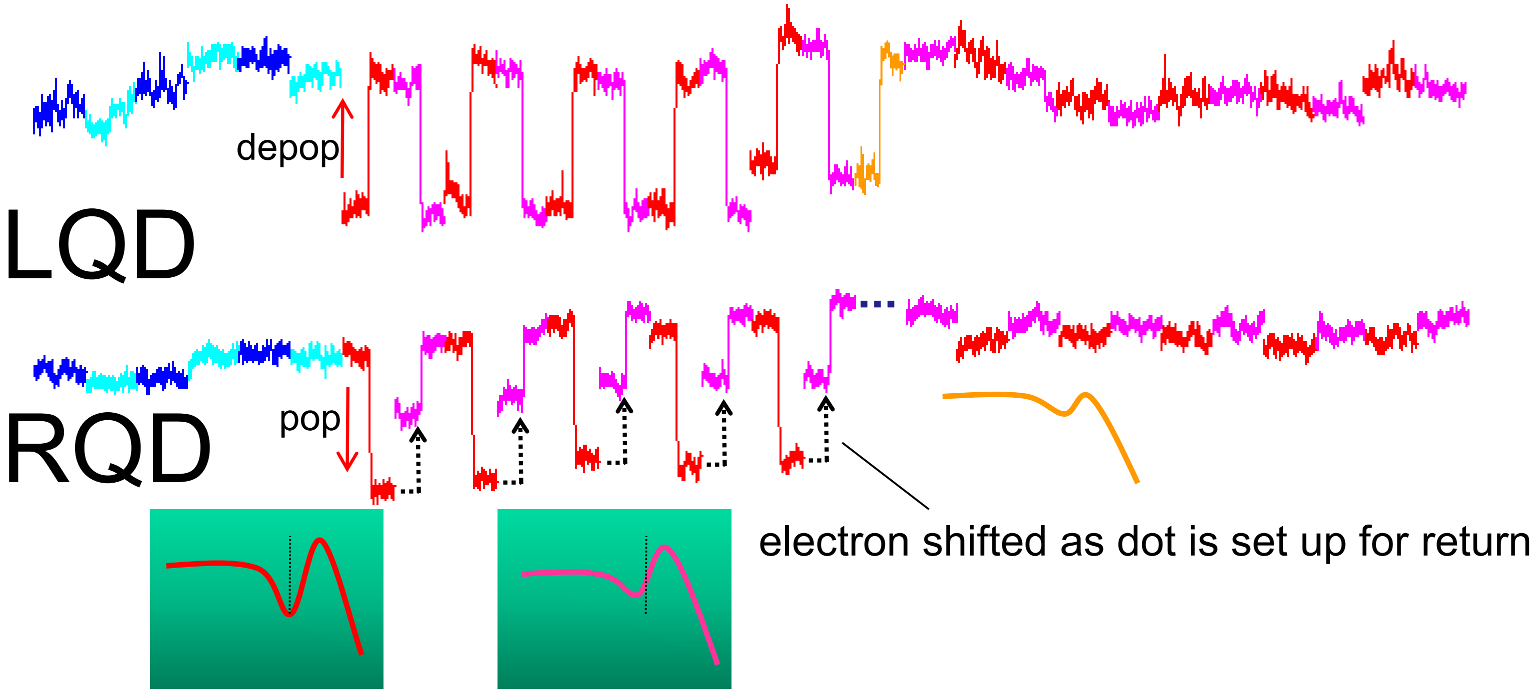


- RQD starts with one electron
- LQD empty
- Send SAW pulse
  - Electron occasionally gets stuck in channel, but usually reaches other dot

Single-electron "ping pong"



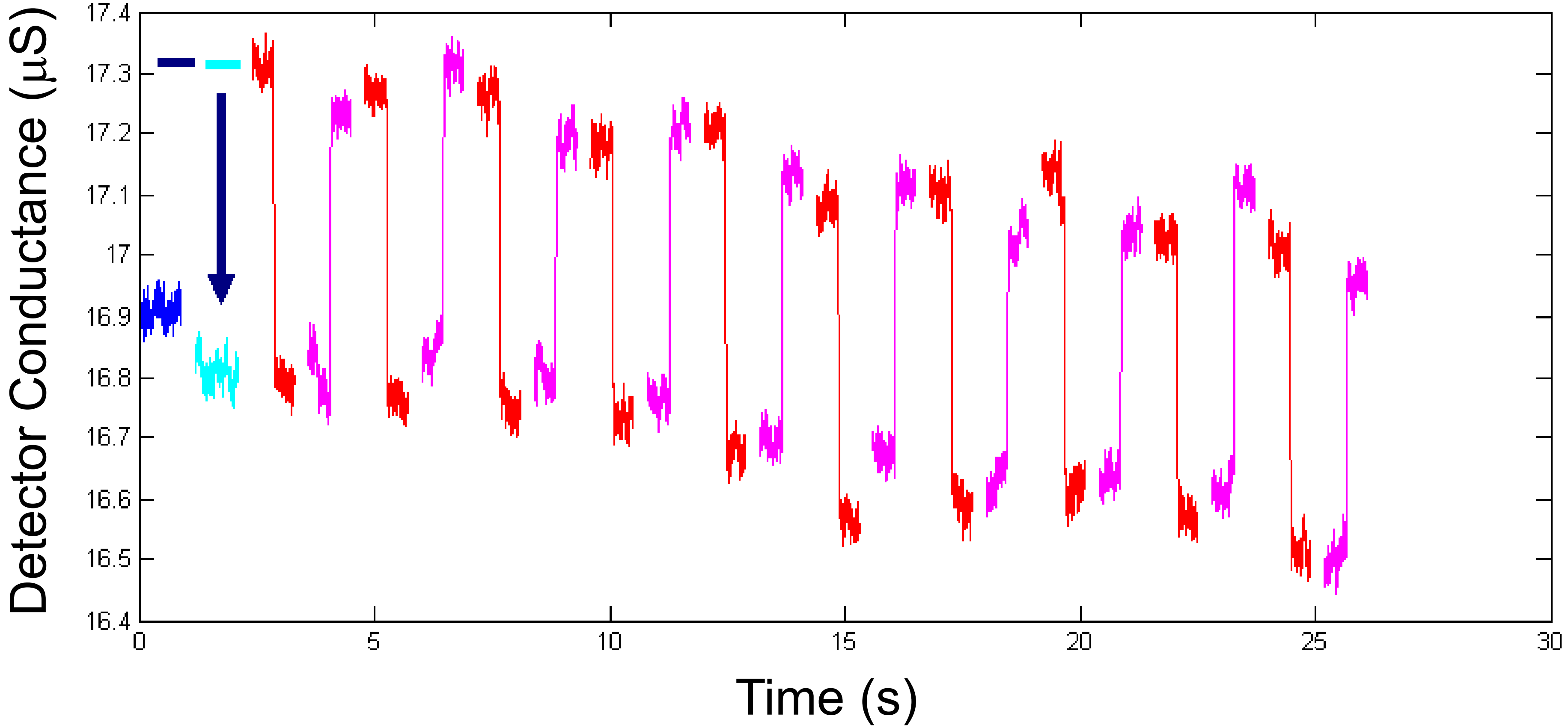




electron shifted as dot is set up for return

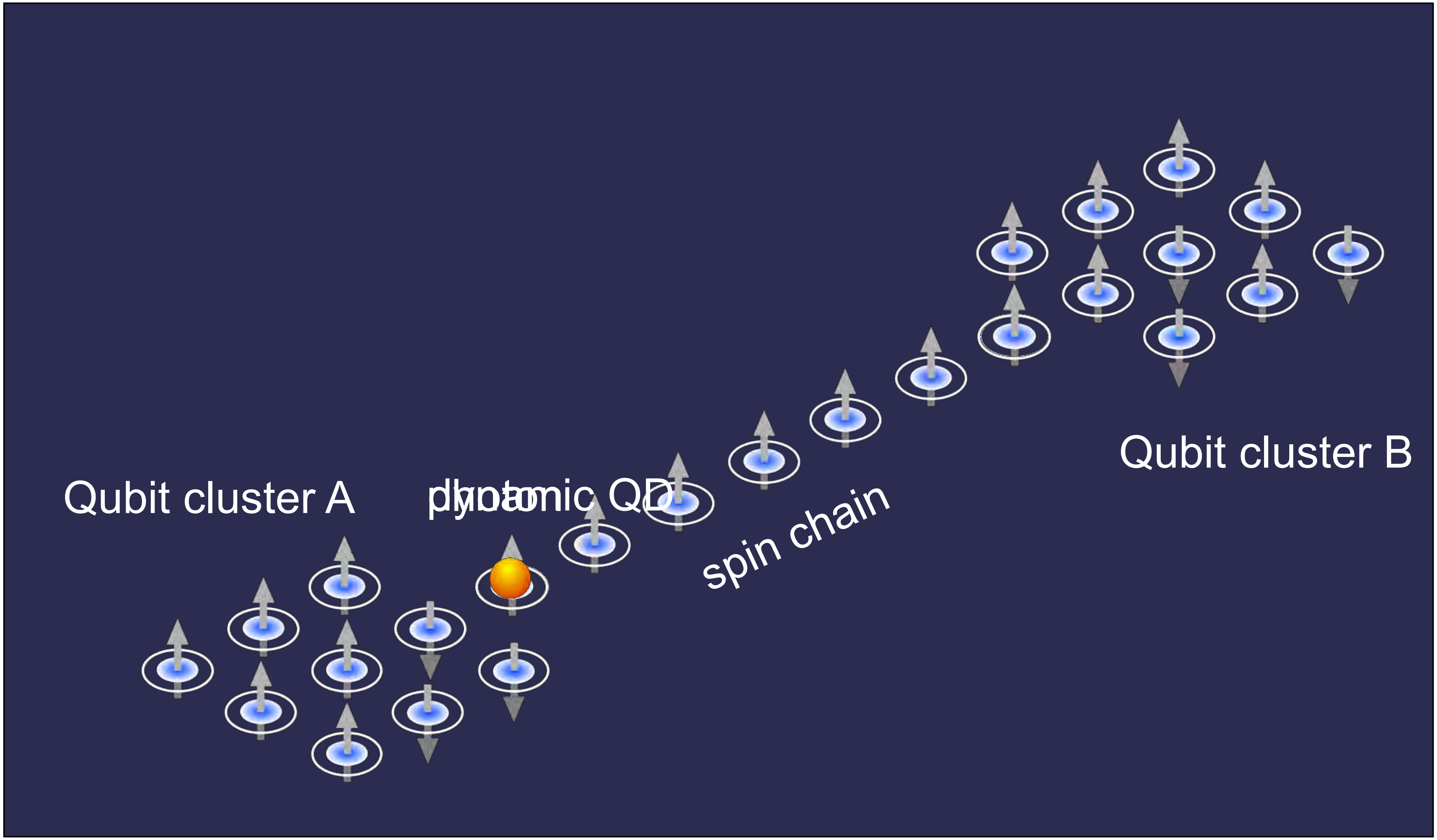
Reliability of transfer

- Can transfer same electron at least 60 times (0.25mm!) along the channel before it is joined by another from outside

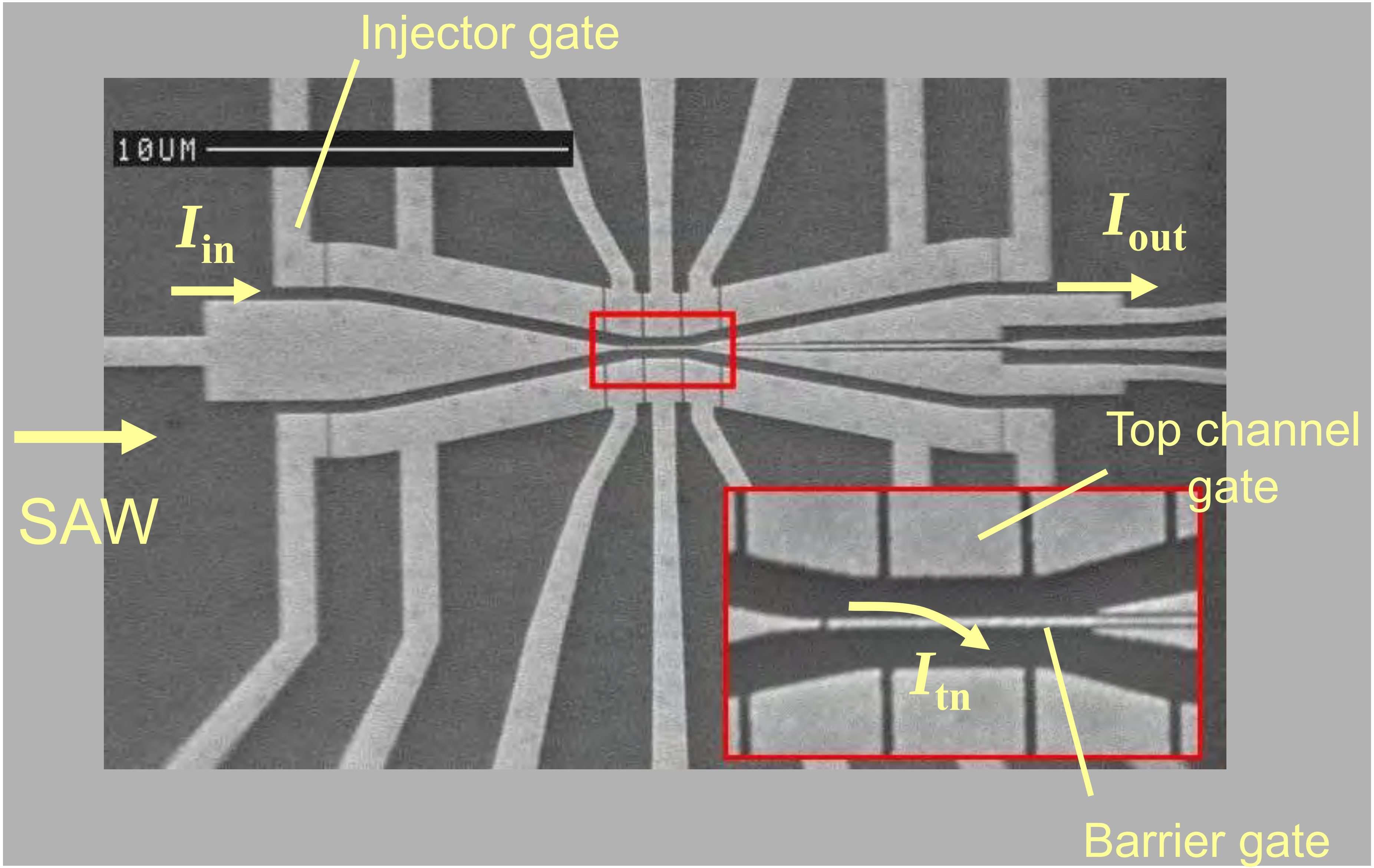


- Next step: convert spin polarisation to photon polarisation
  - we have just finished building a cryogenic microscope for our 300mK cryostat

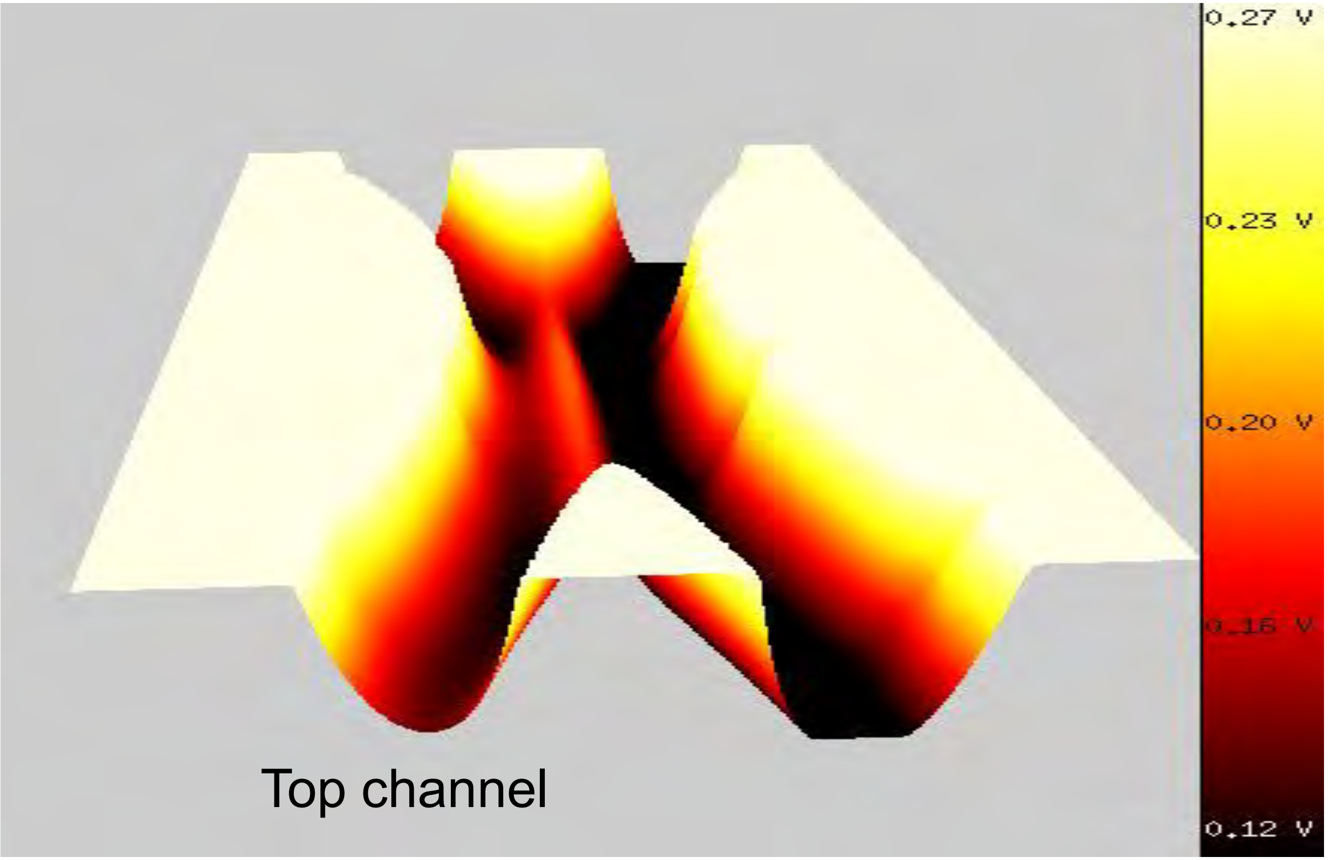
Quantum information transfer



Electron tunnelling out of dynamic dots

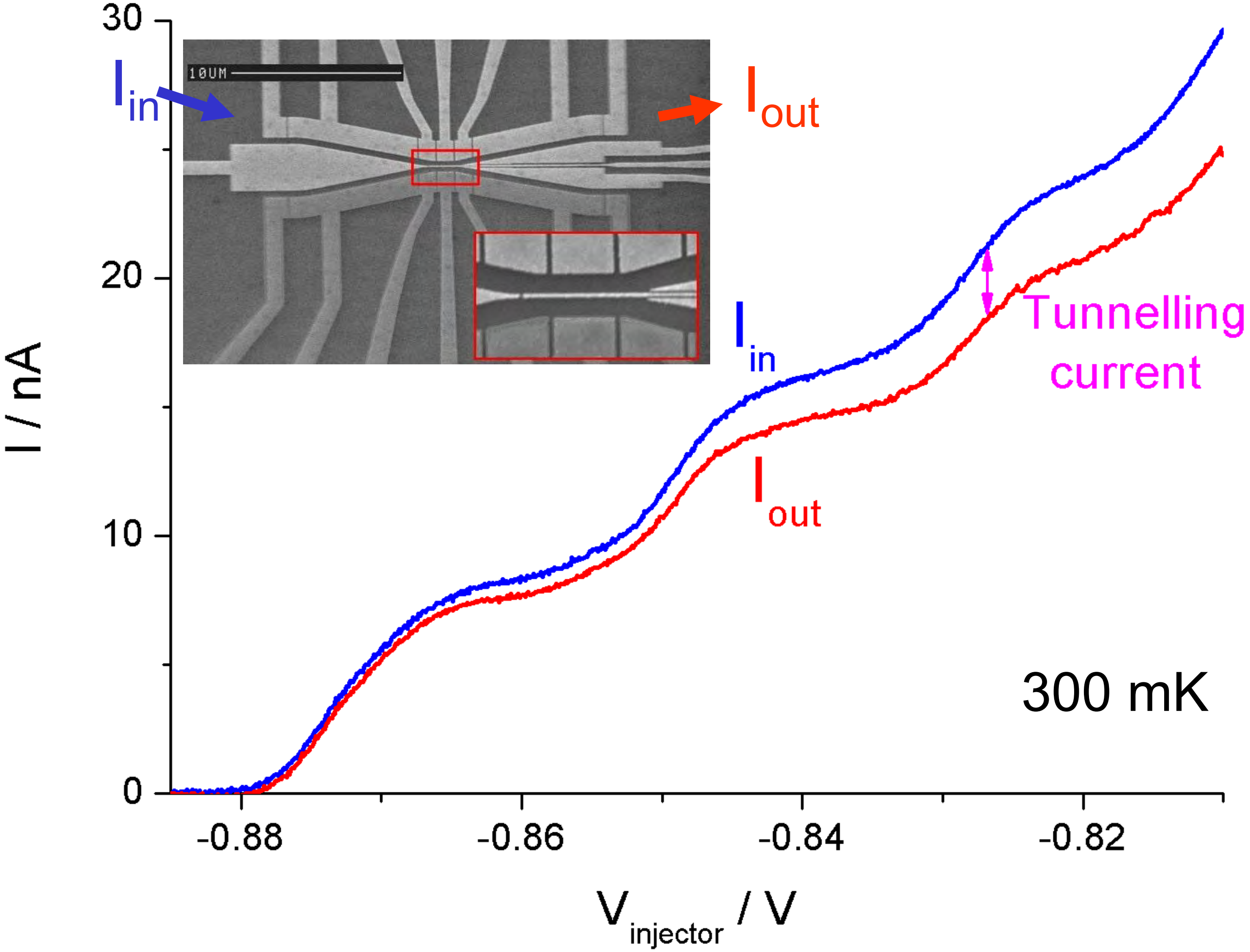


Channel potential landscape

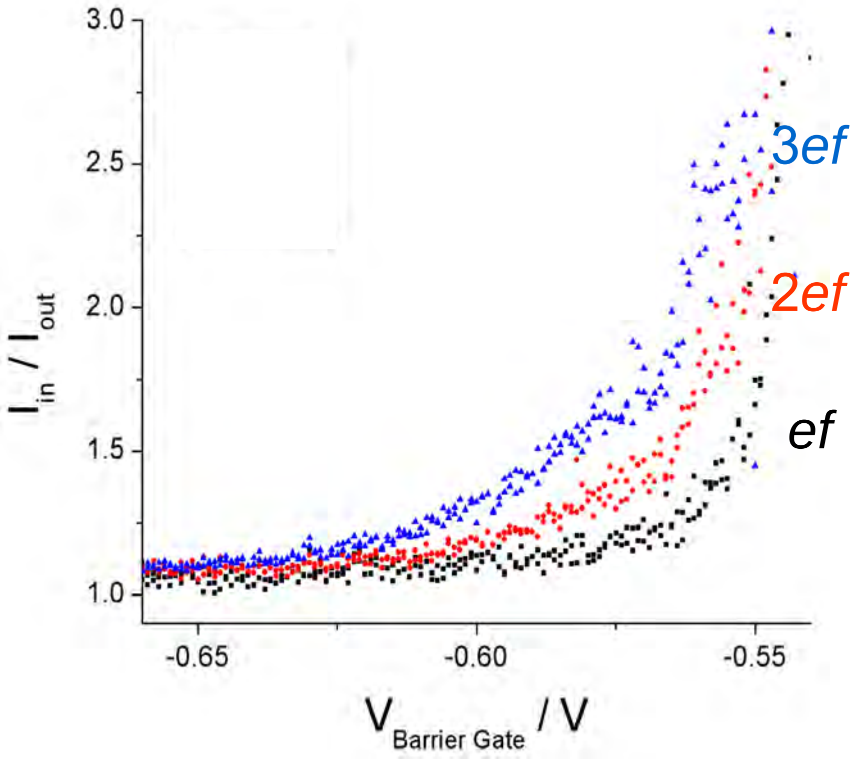


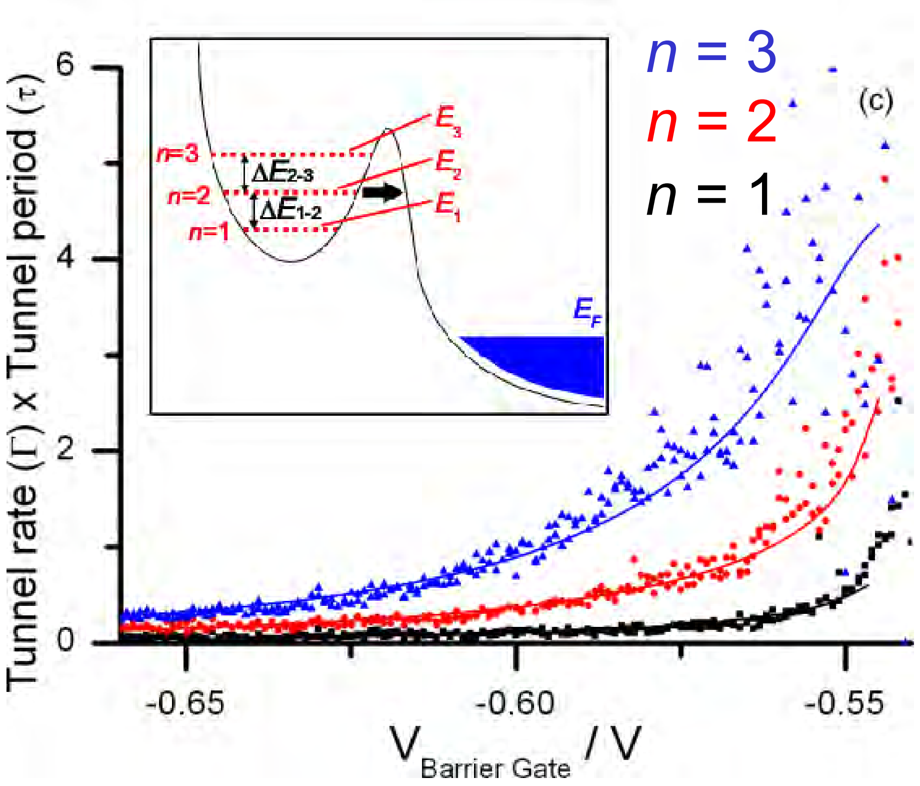
- Potential calculated by solving Laplace’s equation

Measurement of electron tunnelling



Signature of dynamic QD confinement





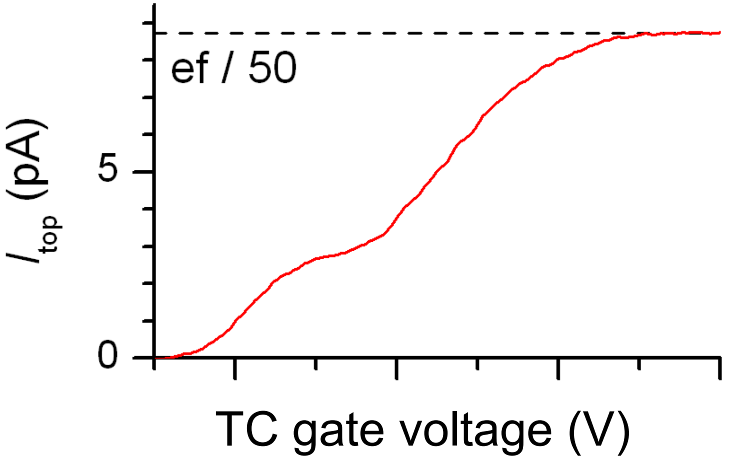
- Ratio I_{in} / I_{out} dependent on number of injected electrons
- Evidence of addition energy

$\Delta\varepsilon_{1-2}$ ~ 2.6 meV

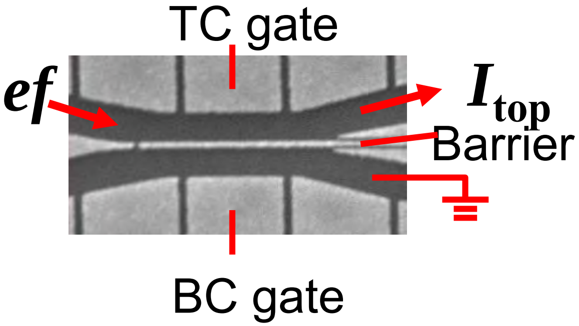
$\Delta\varepsilon_{2-3}$ ~ 14 meV

Astley *et al.*, PRL **99**, 156802 (2007)

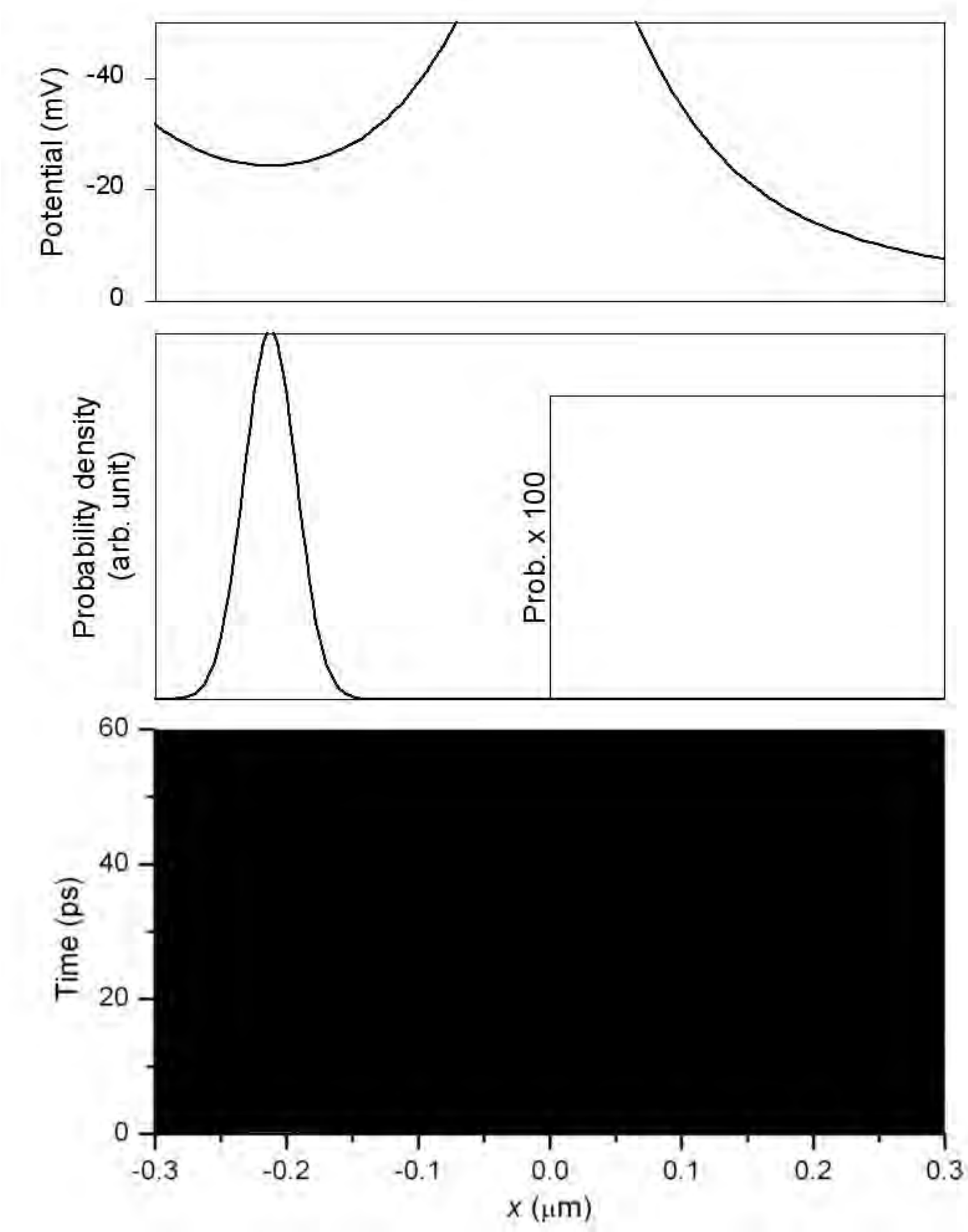
Behaviour of tunnel current



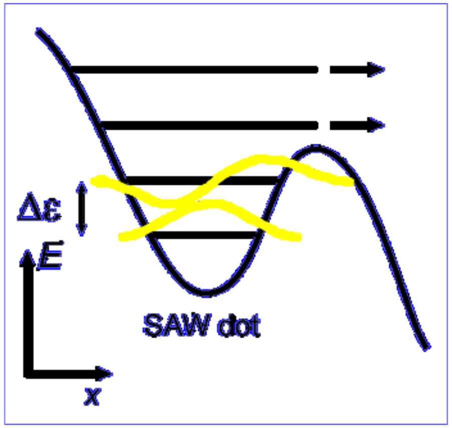
TC gate voltage (V)



Modelling



- Solve *t*-dependent Schrödinger Eqn (in 1D or 2D)
- Realistic gate potentials

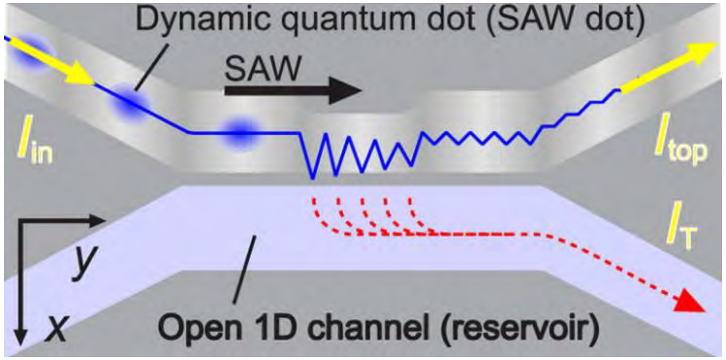


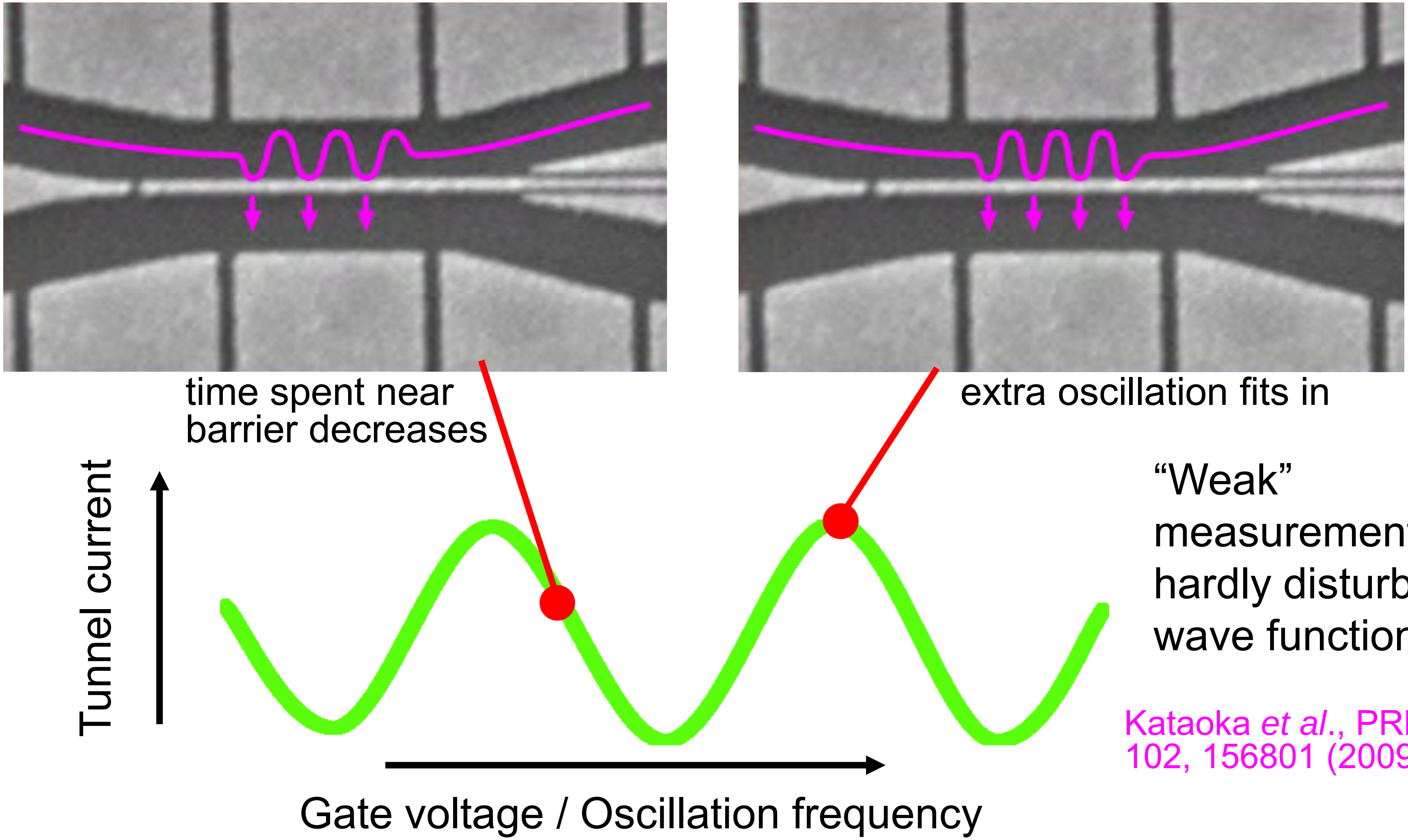
← Coherent oscillations

← All but lowest 2 modes escape rapidly

A. L. Thorn, "Electron dynamics in surface acoustic wave devices", PhD thesis, Cambridge University (2009)

Tunnel-current oscillations





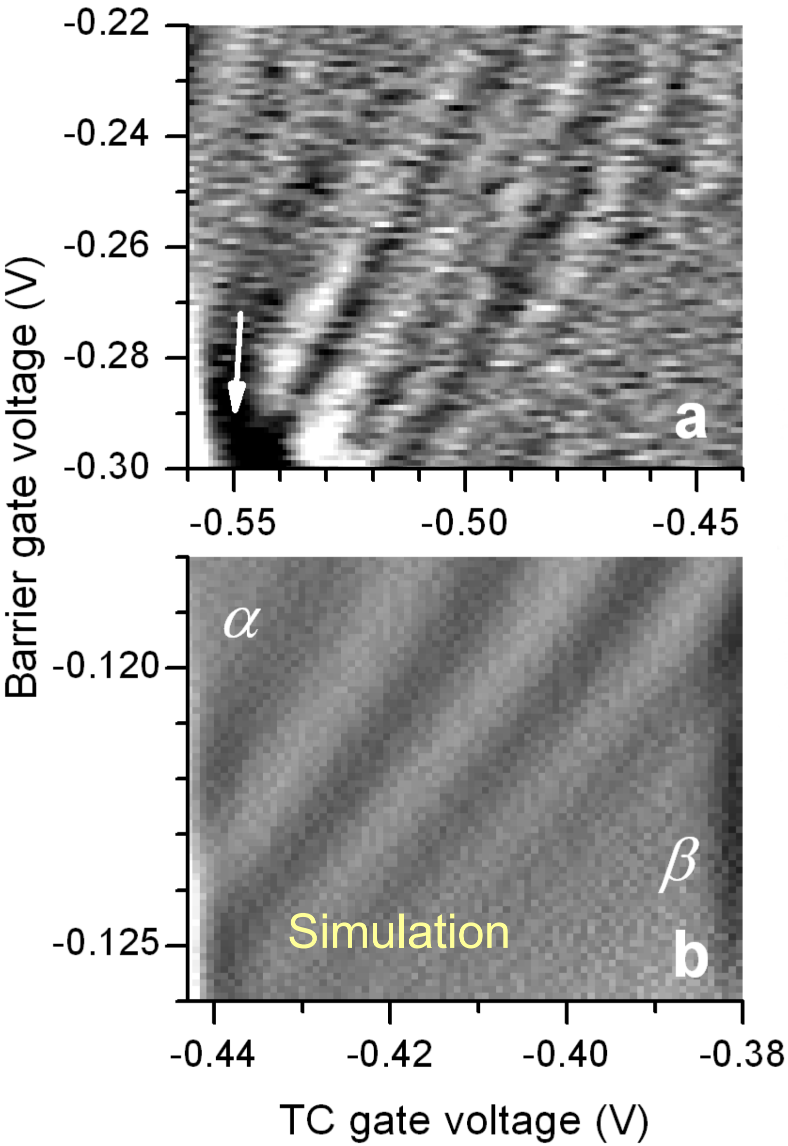
time spent near barrier decreases

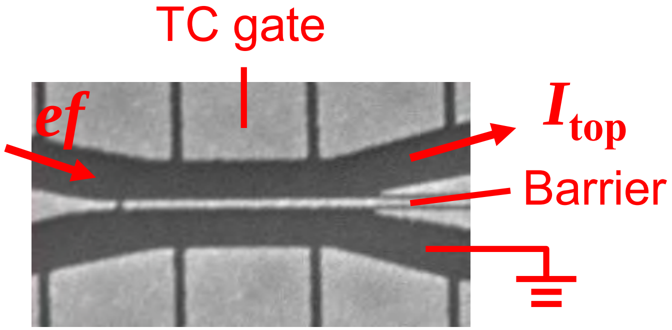
extra oscillation fits in

“Weak” measurement – hardly disturbs wave function

Kataoka *et al*., PRL 102, 156801 (2009)

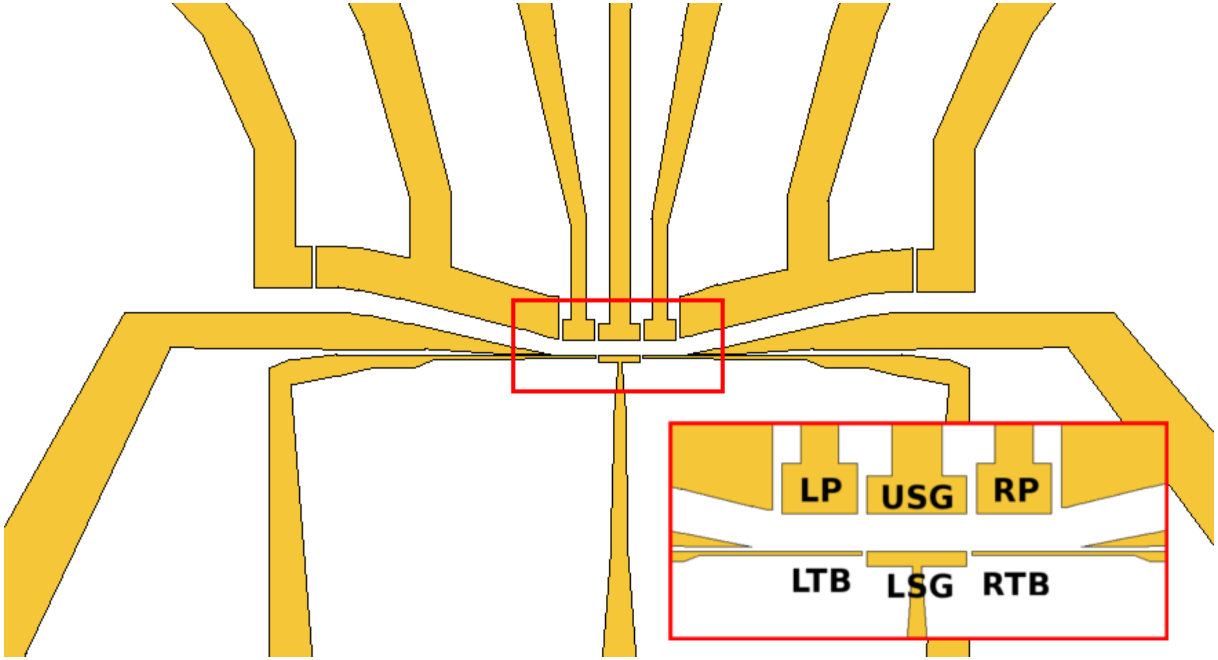
Effect of gates





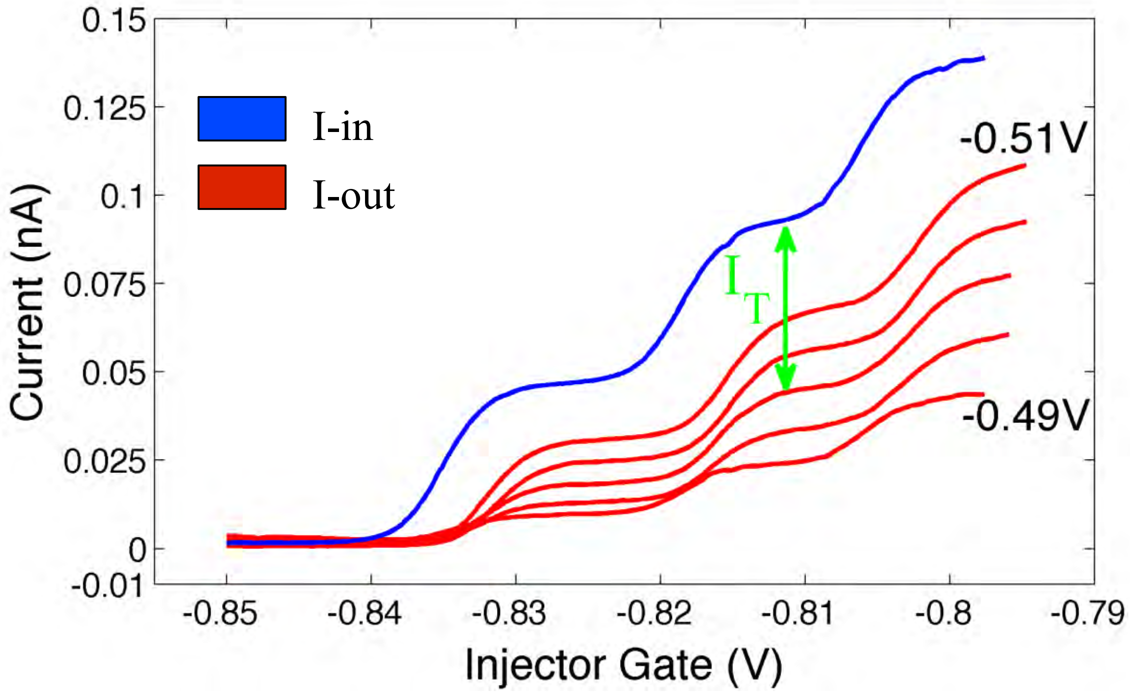
- Simulation using potential calculated by solving Laplace’s equation
- Sweeping to a more negative value:
  - TC gate: Δε decreases
  - Barrier gate: Δε increases

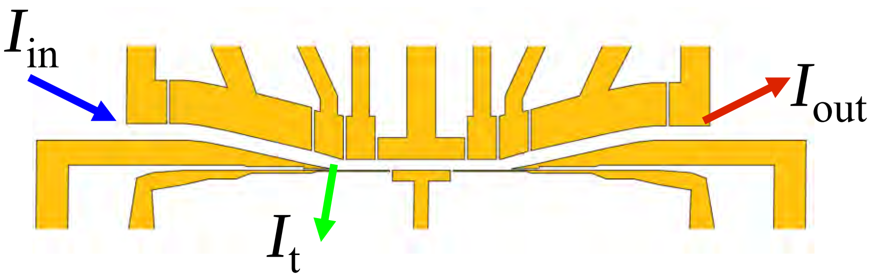
Double-barrier device



- Single 1D channel with two tunnelling regions
- Tunnel coupling separately controlled by respective plungers
- Single-electron dots injected from the left and measured at both the upstream and downstream tunnel barriers

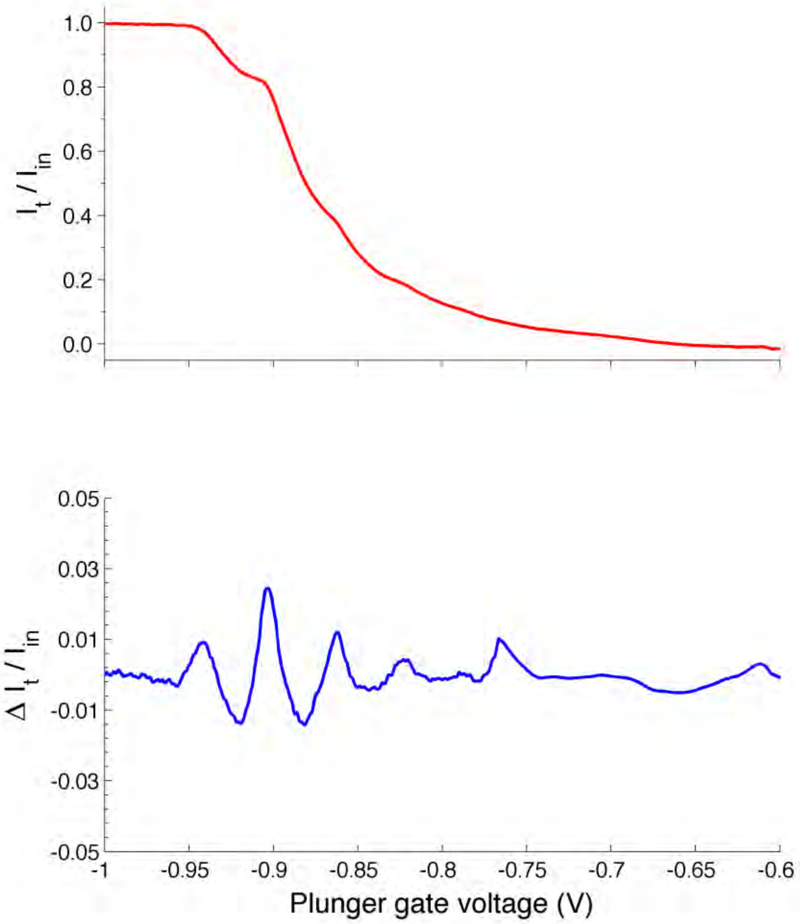
Double-barrier device: tunnel current





- Injector gate can be tuned to low-*ef* plateaux
- For a range of barrier voltages, the exit current I_{out} shows reduced plateaux
- The exit current is reduced by the barrier-dependent tunnel current

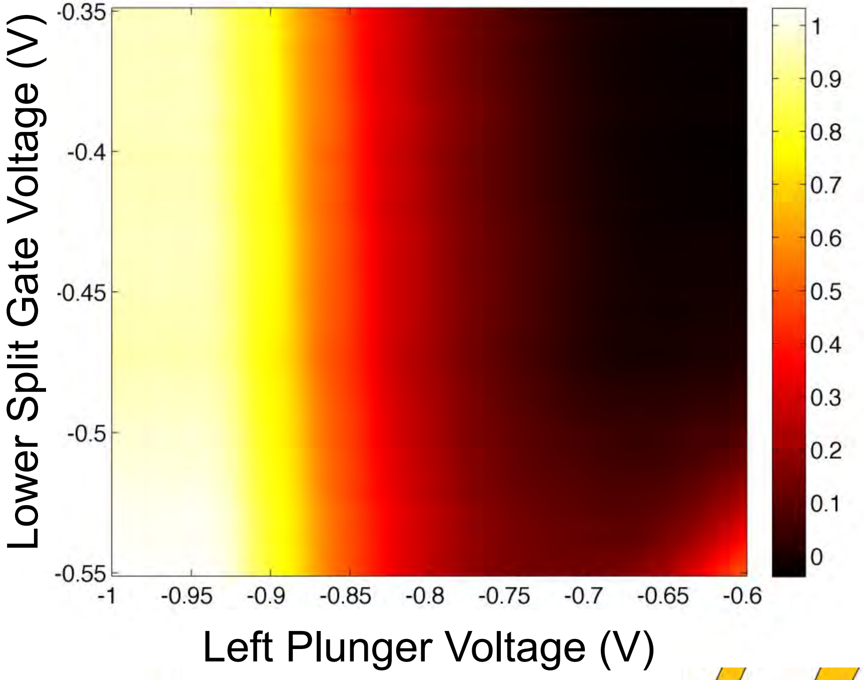
Double barrier: tunnel-current oscillations



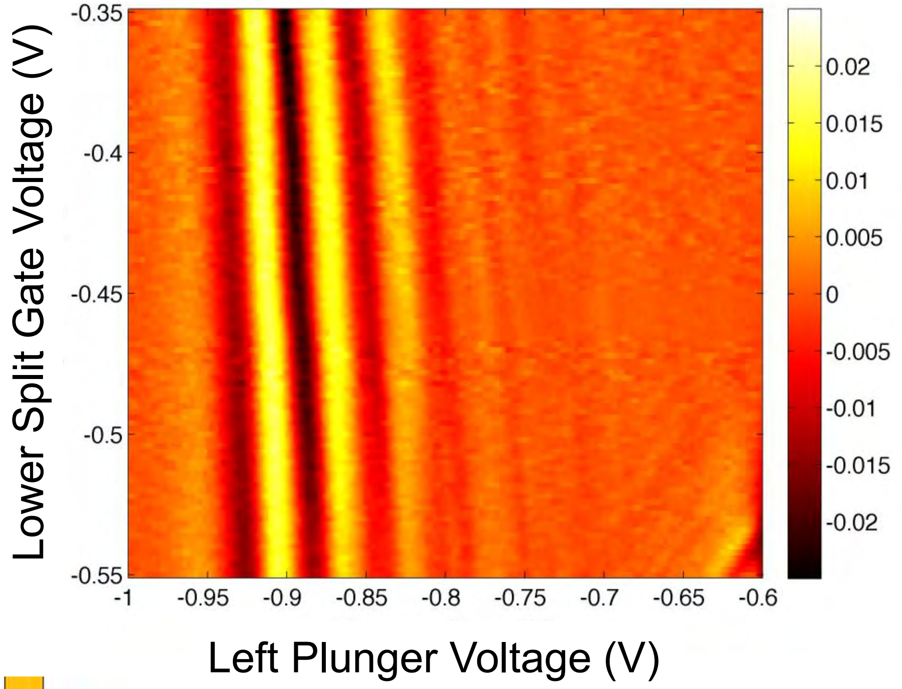
- Typical current variation as plunger gate is swept for a fixed barrier
- Tunnel current varies from 0% to 100% of injected current
- Removal of slowly-varying contributions reveals periodic oscillations

Coherent Oscillations – First Barrier

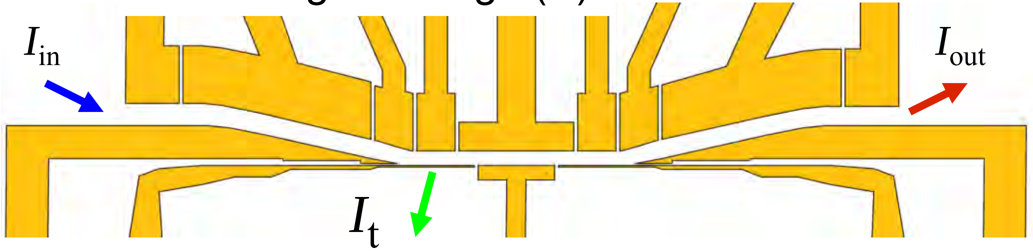
- Single-electron QDs injected from left
- Vary nearby gate voltages
- Oscillations appear consistently across large voltage ranges

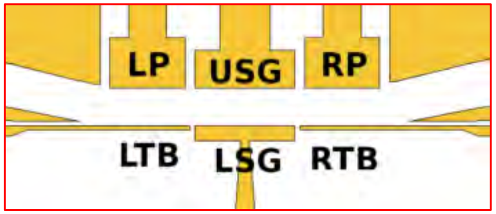


Unfiltered



High-pass filtered

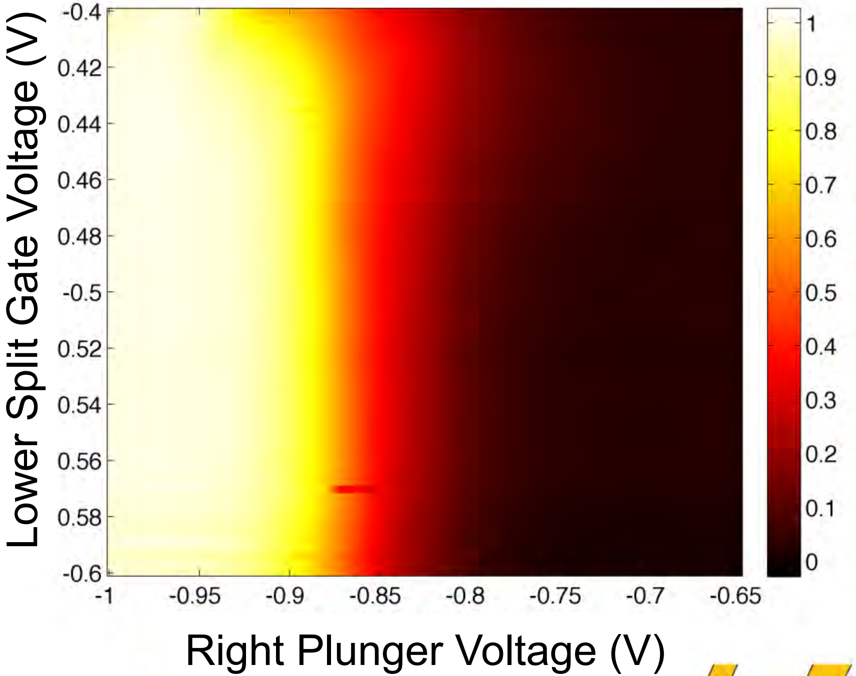




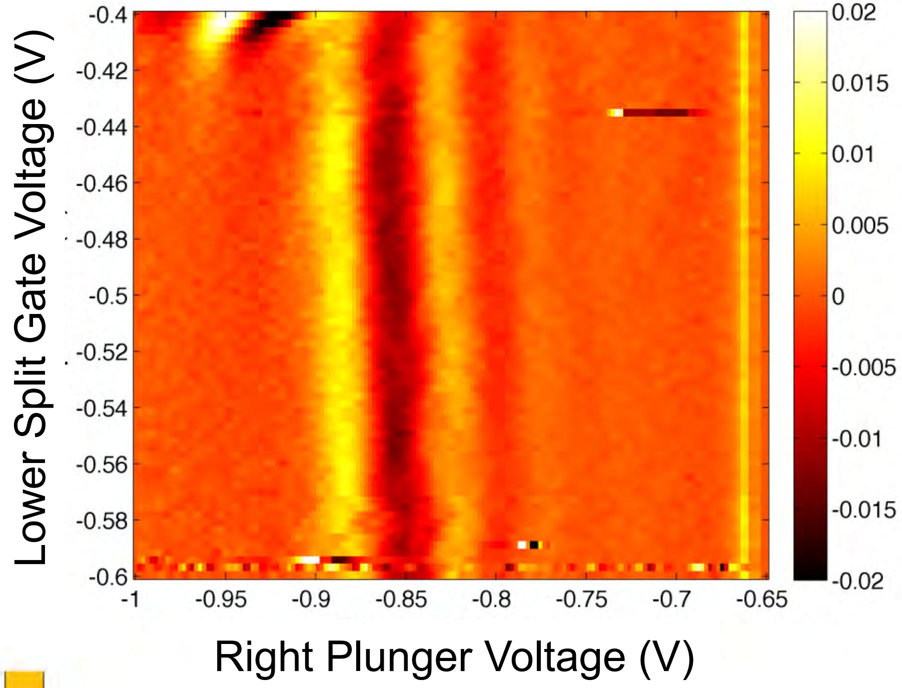
Coherent Oscillations – Second Barrier

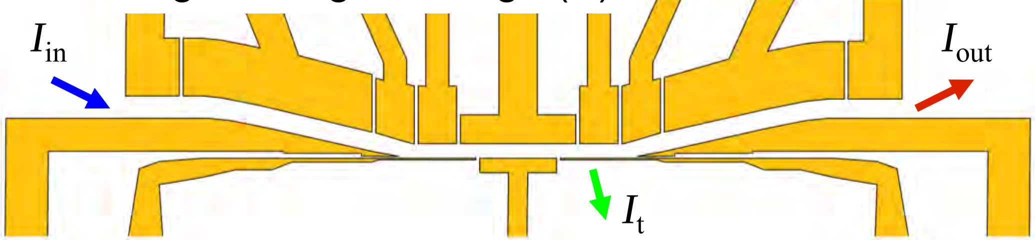
- Single-electron QDs injected from left
- LTB is pinched off to prevent tunnelling
- Tunnelling occurs through RTB

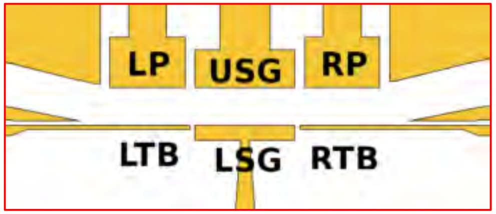
Unfiltered

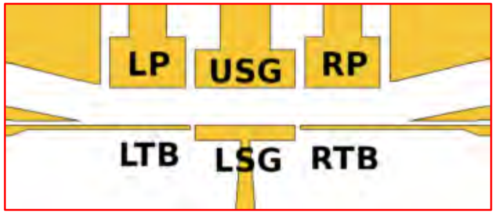


High-pass filtered

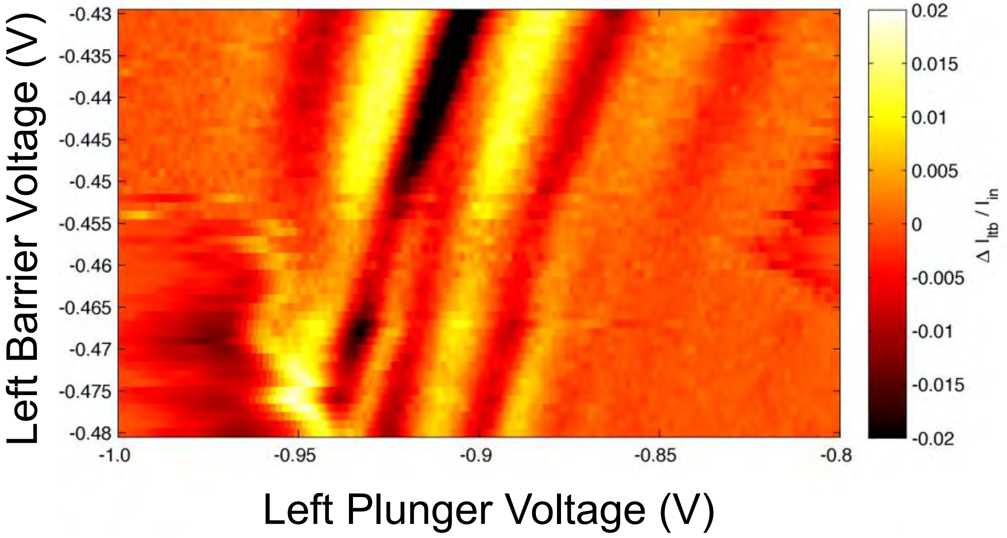


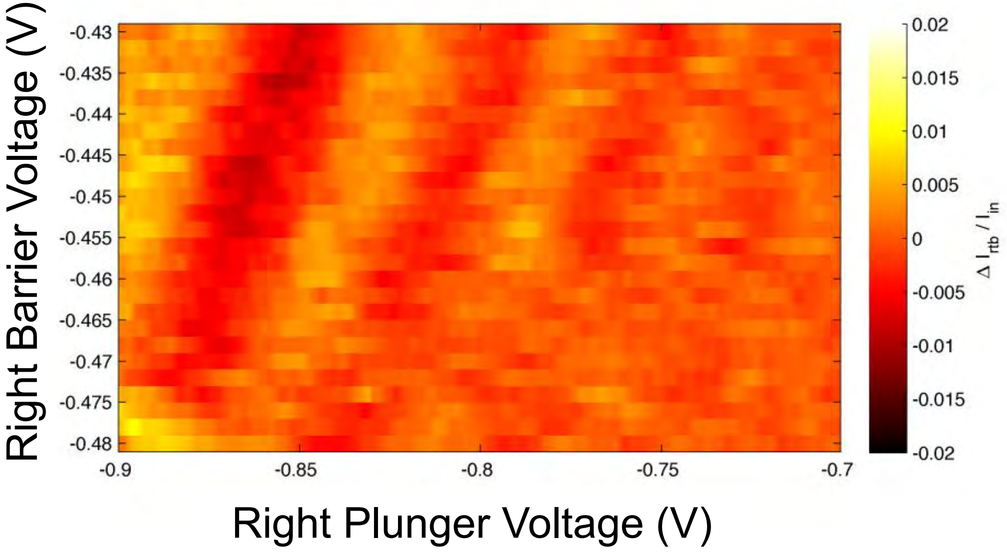






Comparison of barriers

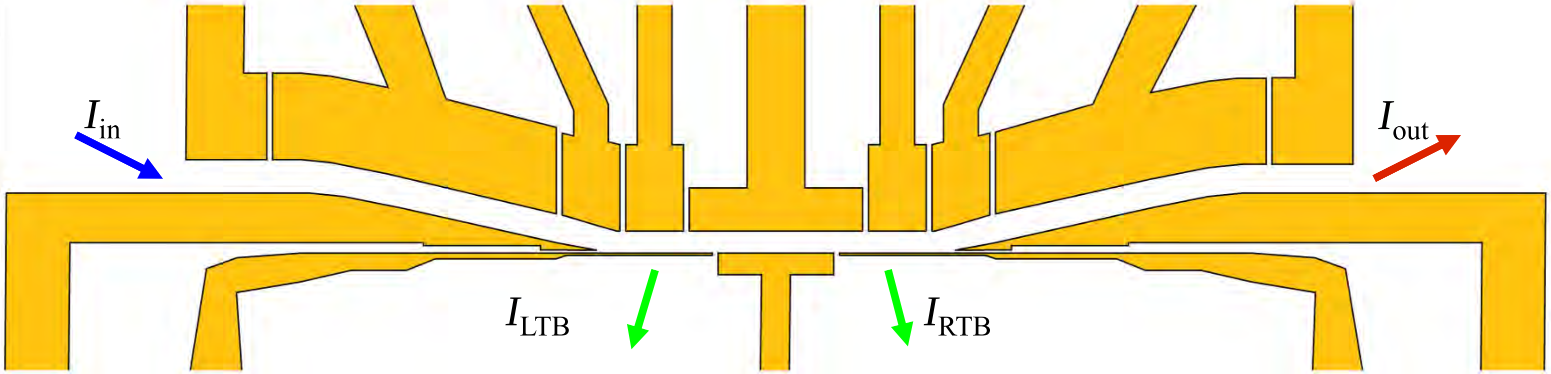




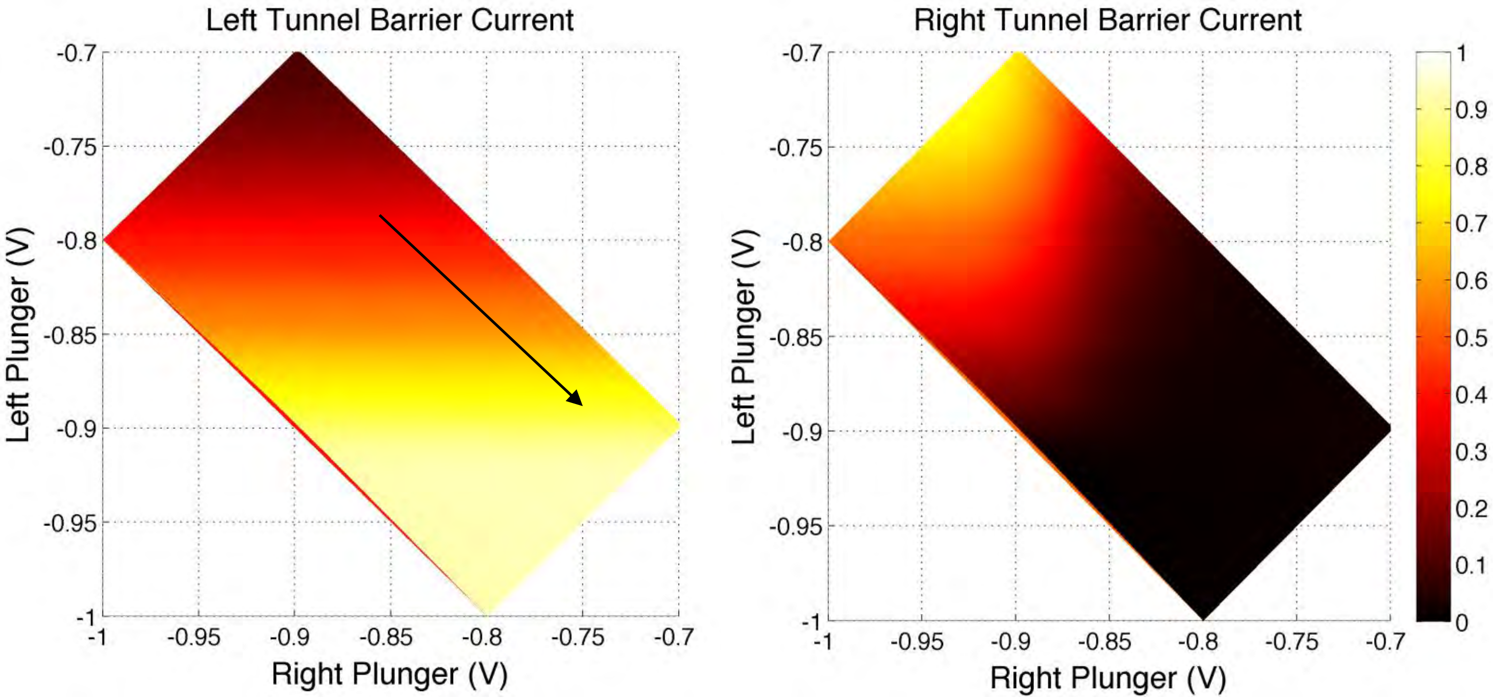
- Measure tunnelling current for each barrier as a function of its own plunger gate
  - when measuring RTB, LTB is pinched off to prevent tunnelling
  - filter out background
- Quite similar oscillations for each

Comparison of tunnelling currents

- Gate voltages are arranged to allow tunnelling through both upstream and downstream tunnel barriers
- Both plungers are swept simultaneously so that filtering along the sweep direction will reveal oscillations caused by either plunger

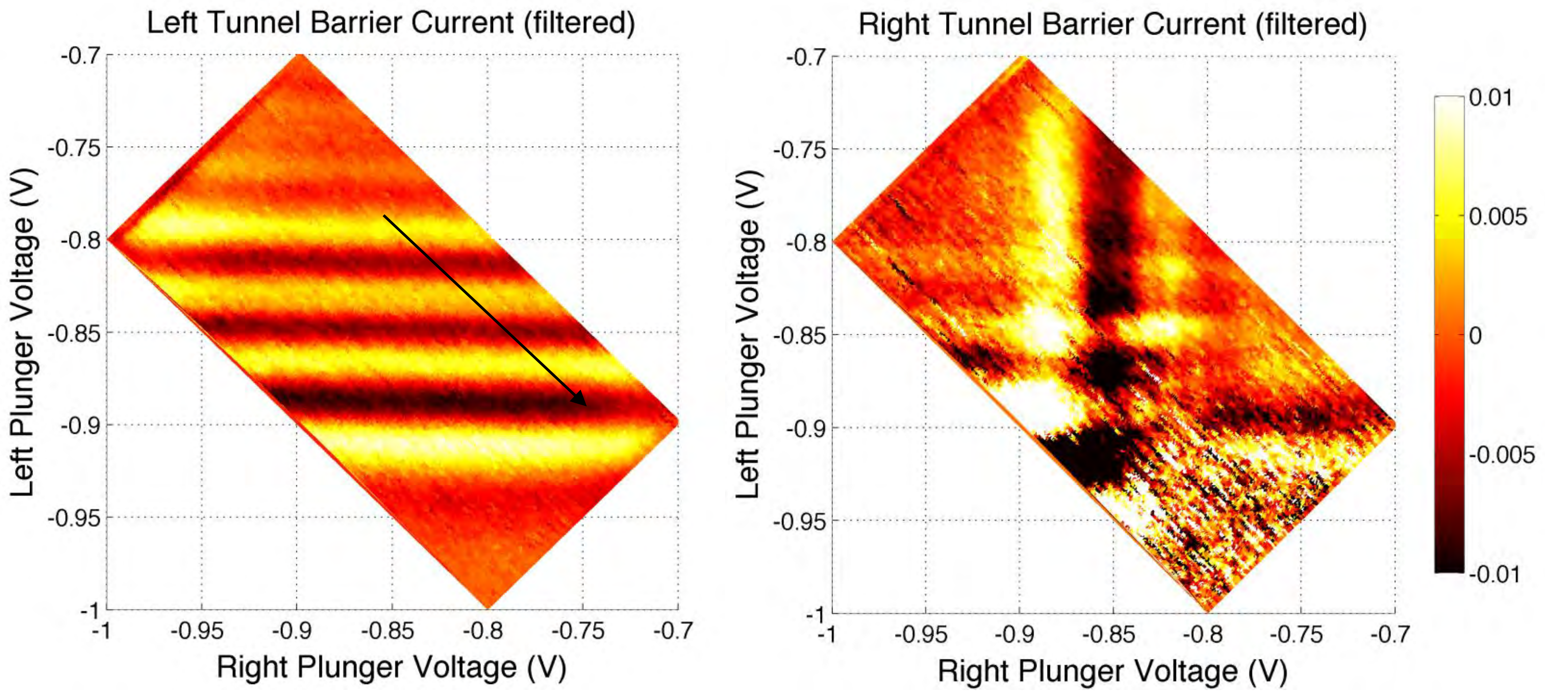


Comparison of tunnelling currents



- I_{LTB} exhibits normal transition to 100% of I_{in}
- I_{RTB} responds as expected
  - reduced by I_{LTB}, as that current has already left the channel

Comparison of tunnelling currents

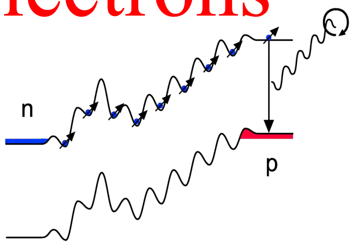


- Oscillations in I_{LTB} appear as previously measured, with no dependence on the right plunger
  - not cross-capacitance
- I_{RTB} shows significant dependence on both plungers, leading to a checkerboard oscillation pattern

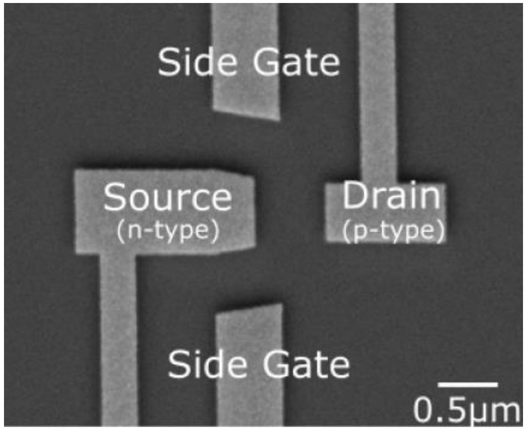
Coherence length

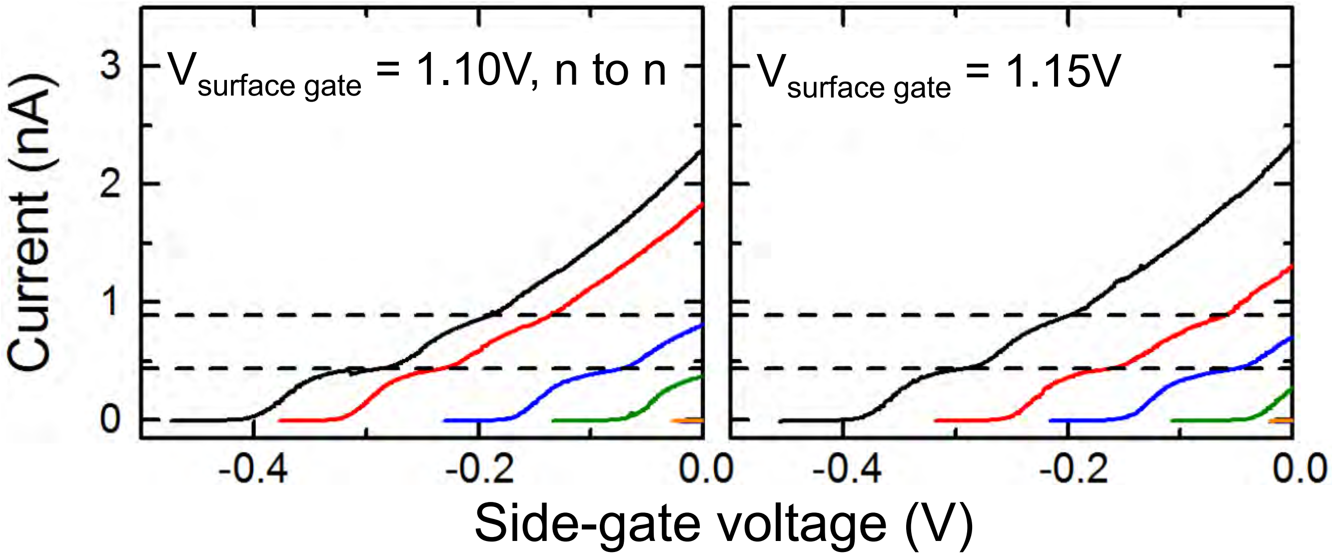
- Oscillations in RTB tunnelling current occur as a function of the *left* plunger
- Oscillations were initialised in the left region, so they must have continued for at least part of the left region and the central region (1.5–3 μm)
  - suggests a coherence time of ~500ps or more (SAW travels 1μm in 300ps)

Generating photons from SAW-pumped electrons

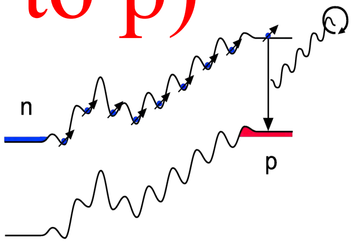


- The SAW can pump electrons uphill
  - can it pump them into a sea of holes?
- Cannot dope a wafer differently in different places, so use undoped wafer and induce electrons and holes
  - we have developed quite reliable ohmic contacts for e and h
  - gates on surface bring electrons and/or holes within 1µm
  - quantised current n to n (two regions of electrons)

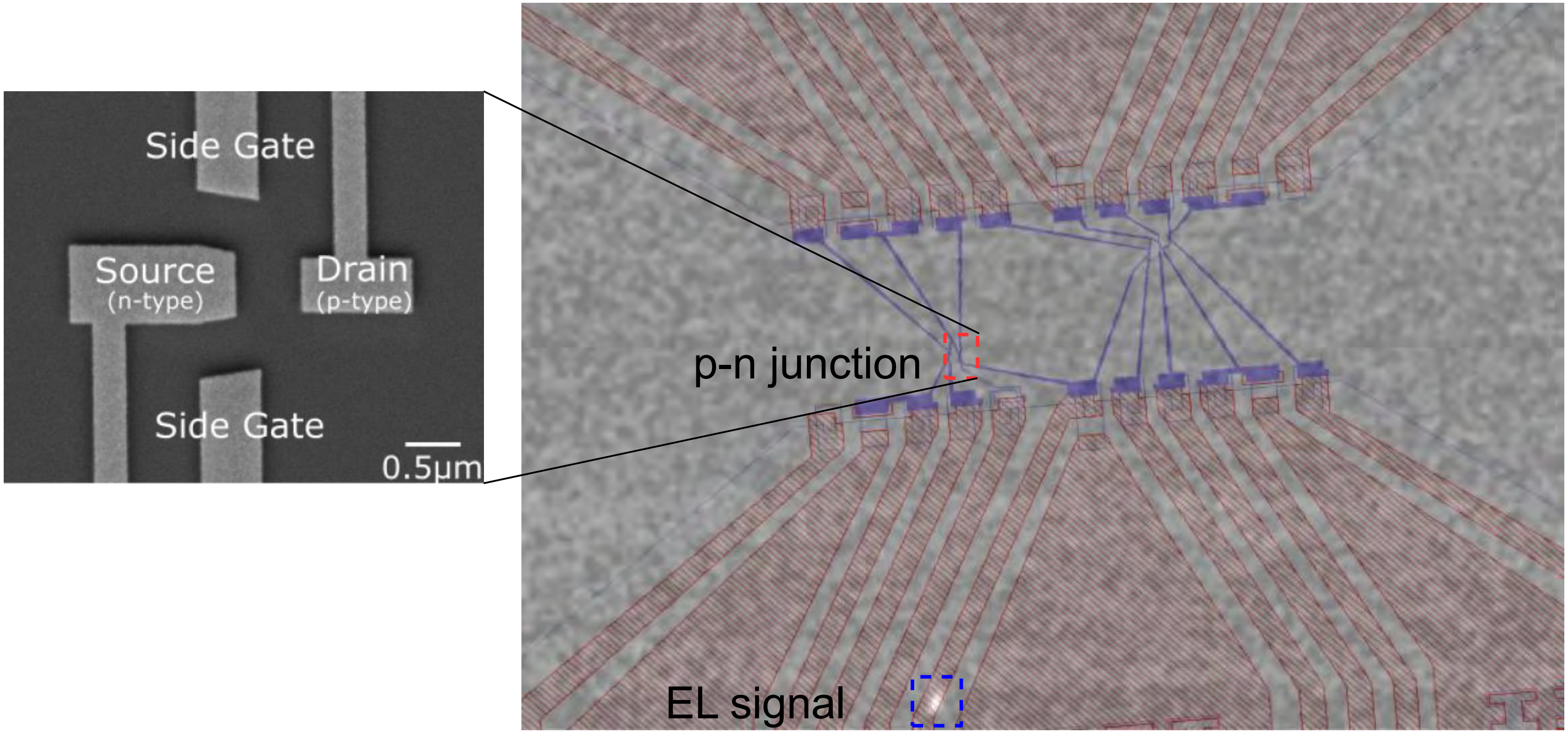




Pumping from electrons to holes (n to p)

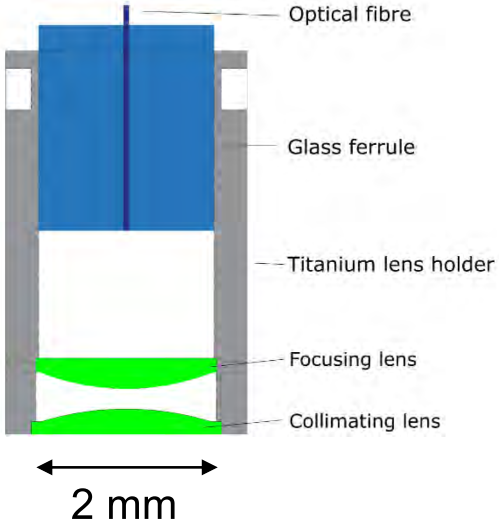


- Induce electrons and holes close together
  - forward-bias the p-n junction to reduce barrier slope
  - SAW can pump electrons into conduction band above the holes
  - so far, light comes out from the wrong place!
  - need to etch around junction to confine electrons in same place as holes until they recombine

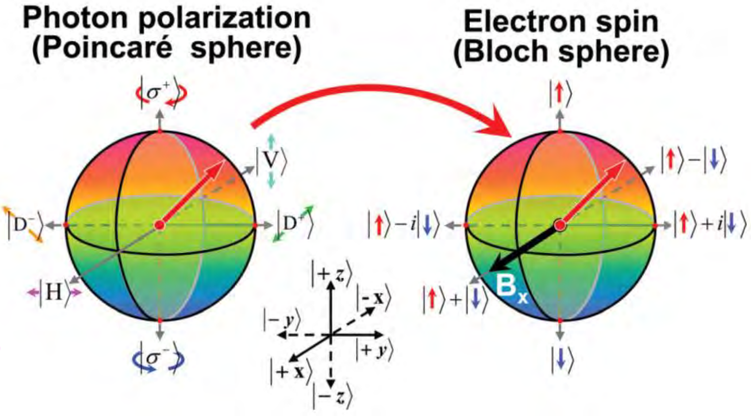


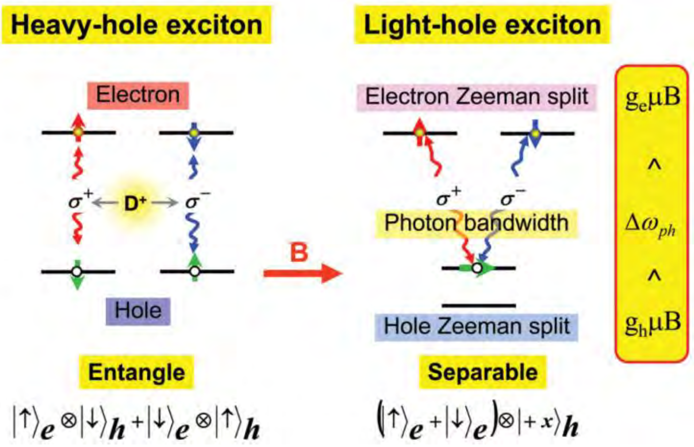
^{3}He microscope

- We have constructed a scanning optical microscope
  - works in ^{3}He top-loading cryostat at $T \geq 300$ mK
  - optical fibre, piezo stage, 1 μm resolution
  - should preserve polarisation (with calibration)
  - sample holder (and coax cables) is fixed
  - lens assembly is scanned
  - available for other applications…



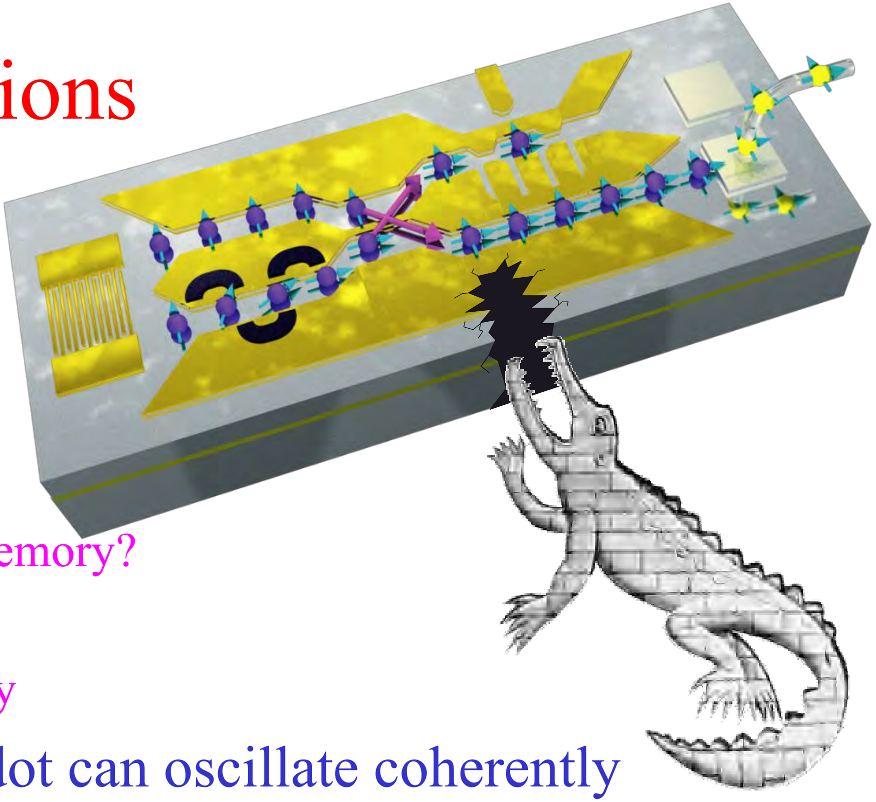
Conversion between photon and electron qubits





- Convert electron's spin to circular polarisation of a photon
  - absence of the hole is information that decoheres rapidly (or no-cloning theorem)
  - so cannot convert a spin qubit (superposition) to photon polarisation qubit coherently
- Kosaka showed that can arrange to have all holes in state $|\rightarrow\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$
  - any electron in $\alpha|\uparrow\rangle+\beta|\downarrow\rangle$ can recombine with such a hole, photon will maintain the superposition as $\alpha|\sigma^+\rangle+\beta|\sigma^-\rangle$
  - $g = 0$ for electrons (15 nm $Al_{0.14}Ga_{0.86}As$ QW)
  - use the light (not heavy) holes (large enough g)
  - H. Kosaka, *J. Appl. Phys.* **109**, 102414 (2011), *Nature* **457**, 702 (2009); *PRL* **100**, 096602 (2008); Vrijen, Yablonovitch, *Physica E* **10**, 569 (2001)

Conclusions



- Dynamic dots are interesting objects with applications in quantum computing
  - generate with a SAW in a long channel
- SAWs can transfer an electron back and forth between two dots
  - couple qubits, transfer to/from quantum memory?
  - electron “ping pong”
  - next step: polarise spin and read it optically
- Single electron in a moving quantum dot can oscillate coherently
  - non-adiabatic transition in channel excites electron into combination of ground and first excited states, producing coherent oscillations that persist for more than 500ps
  - tunnelling probability sensitive to dynamics of single-electron wave function in dot
  - inclusion of multiple tunnelling regions allows initialisation of the oscillation phase, which is then detectable at tunnelling regions downstream
  - can repeatedly make a weak measurement that does not collapse the wave function (Schrödinger’s cat still wouldn’t know if it was alive or dead!)
- Electron and hole regions, (single-)photon emission, qubit conversion?