Semiconductor Structures for Quantum Information Processing

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07.01.03

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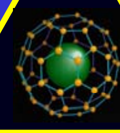

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Quantum Information Processing (QIP)

Quantum Cryptography

Use the principles of quantum measurement to ensure secure information transfer for key exchange etc.

Requires single photon generation and detection at 1.5μm for fibre-optic transmission.

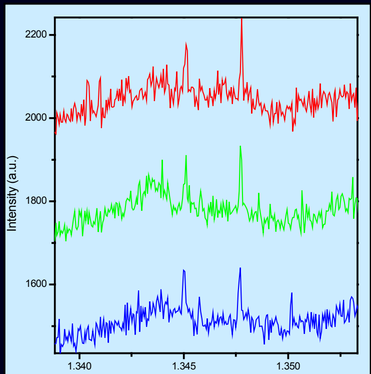
Quantum Computation

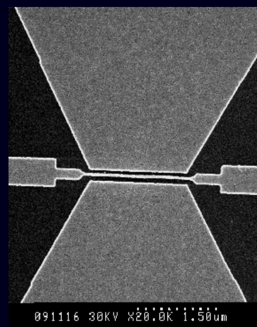
Use quantum entanglement to perform computations such as factoring large numbers and sorting massive databases.

Requires a controllable and measurable two-level system with a high level of coherence.

Recent developments in single-electronics have applications in both fields.

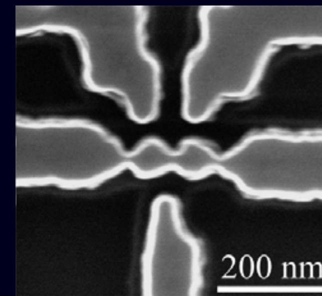
Quantum Information Processing (QIP)

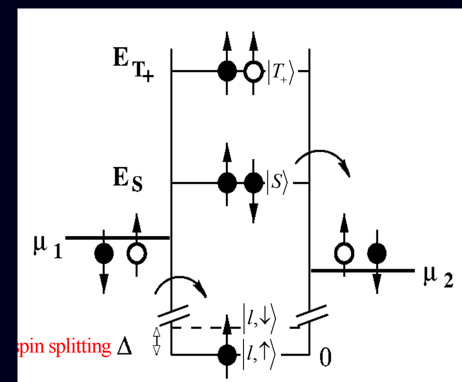


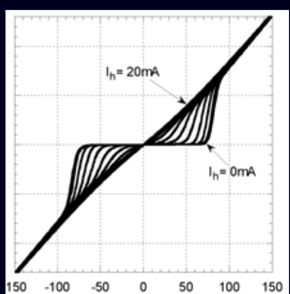


System Types

Photon sources
Photon detectors
Charge qubits
Spin qubits
Magnetic systems
Exciton qubits
Flux systems

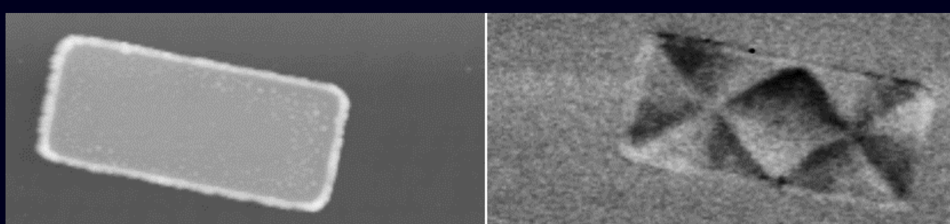






Materials Systems

Nanofabricated semiconductor structures
Self-organised semiconductor dot structures
Carbon nanotubes filled with endohedral fullerenes
Multilayer superconductor structures
Multilayer and nanofabricated magnetic systems



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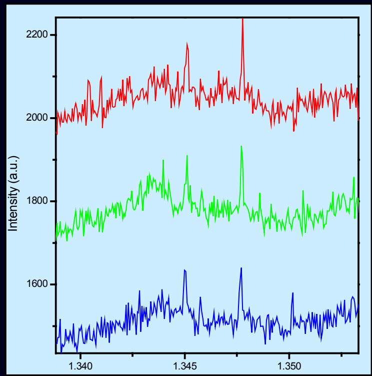

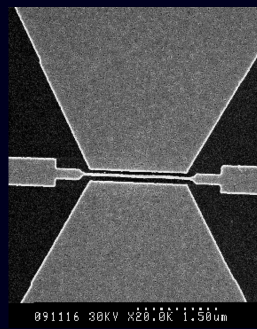

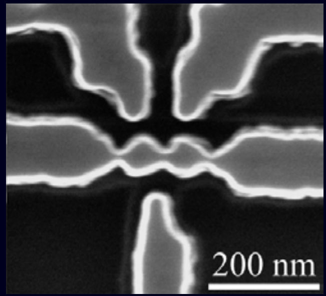

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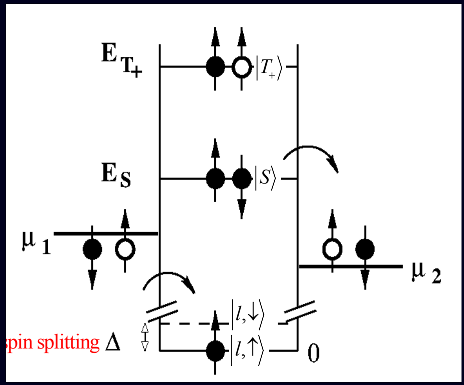

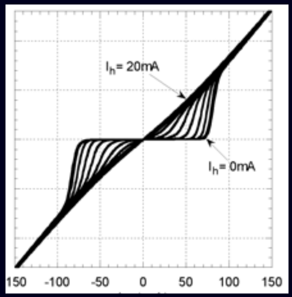

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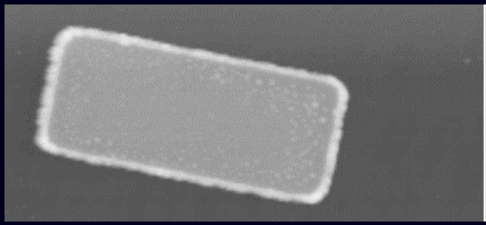
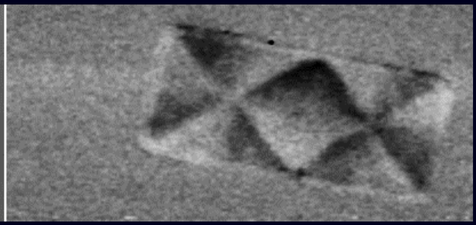
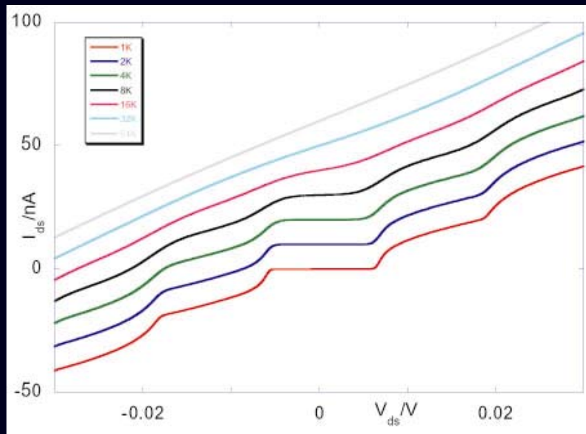
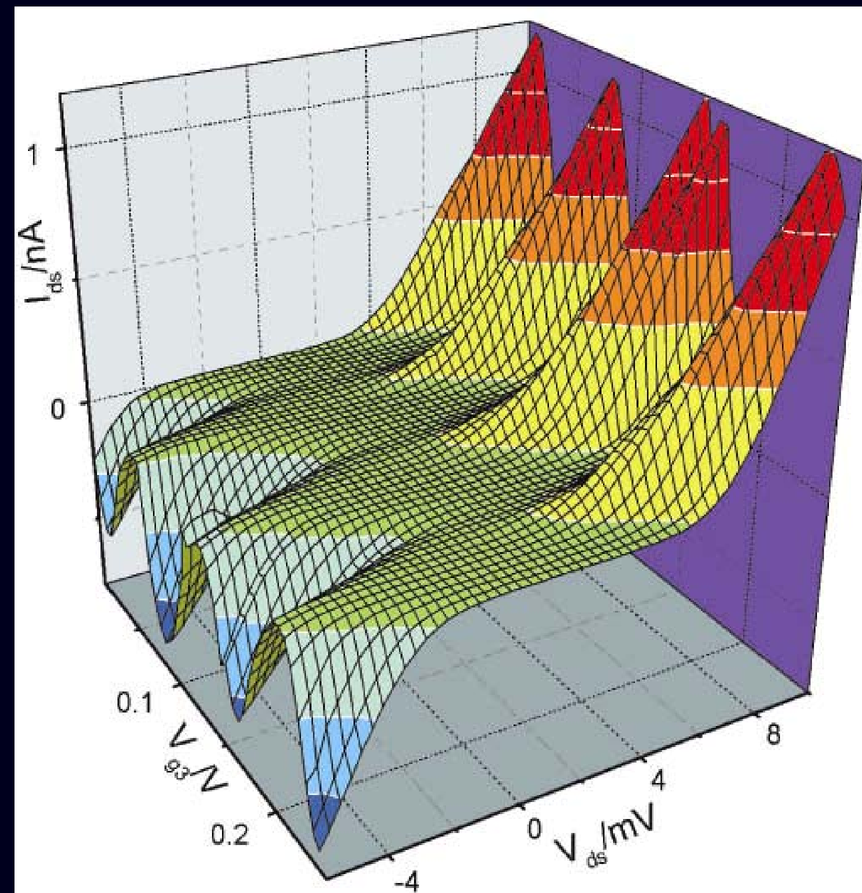


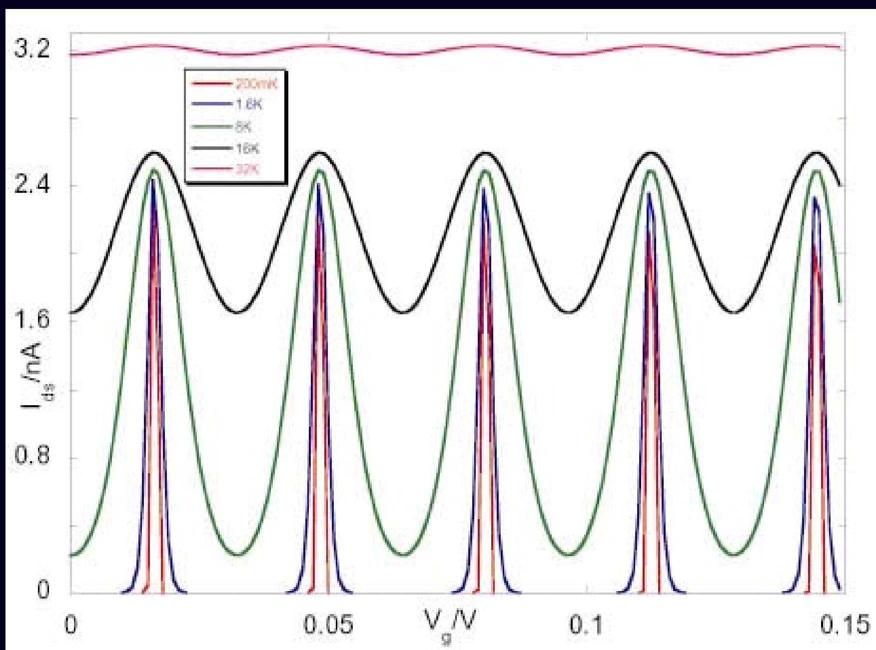


Coulomb Blockade Oscillations

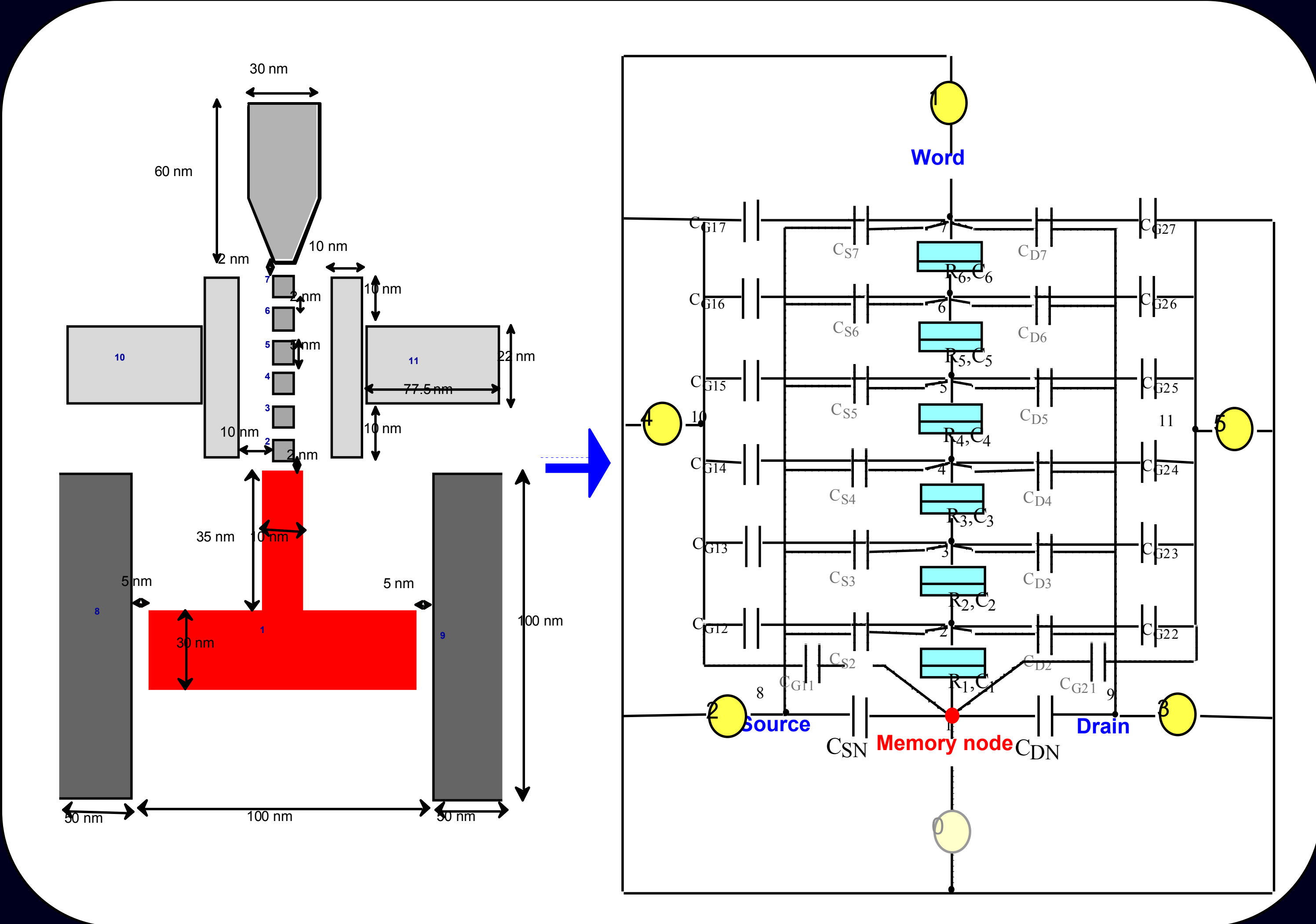


Simulations using CAMSET





Equivalent Circuit



Checklist for quantum computation

1. **State preparation**

   We need a system which is manipulable from the outside

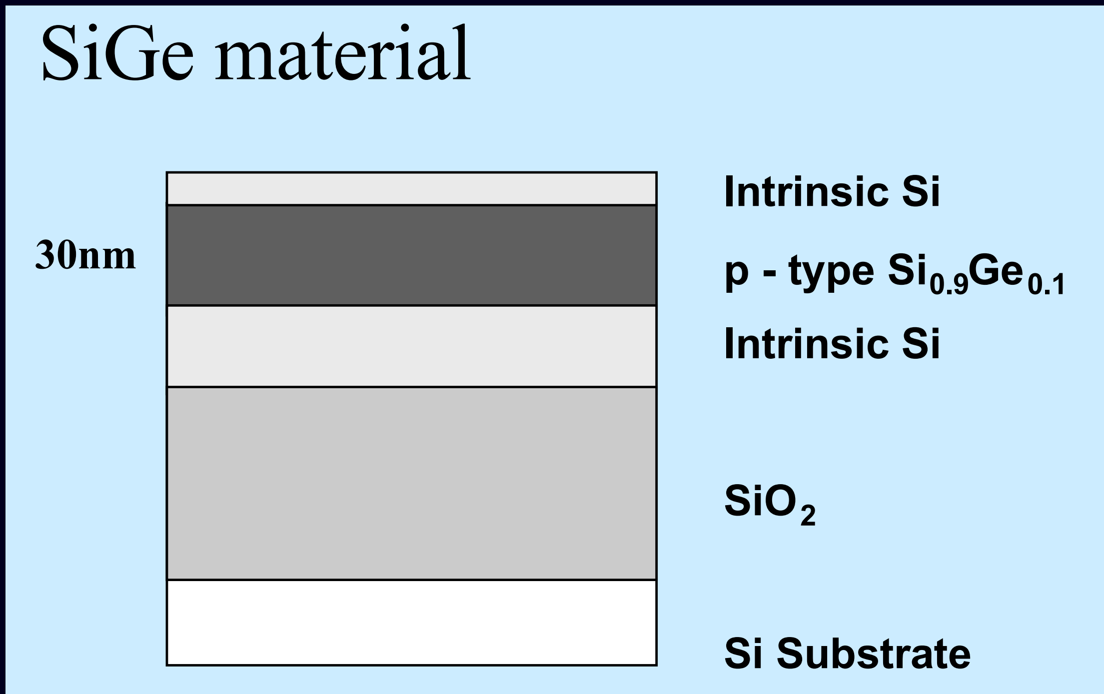
2. **Evolution without decoherence**

   The external interactions must be removed for the duration of the computation stage

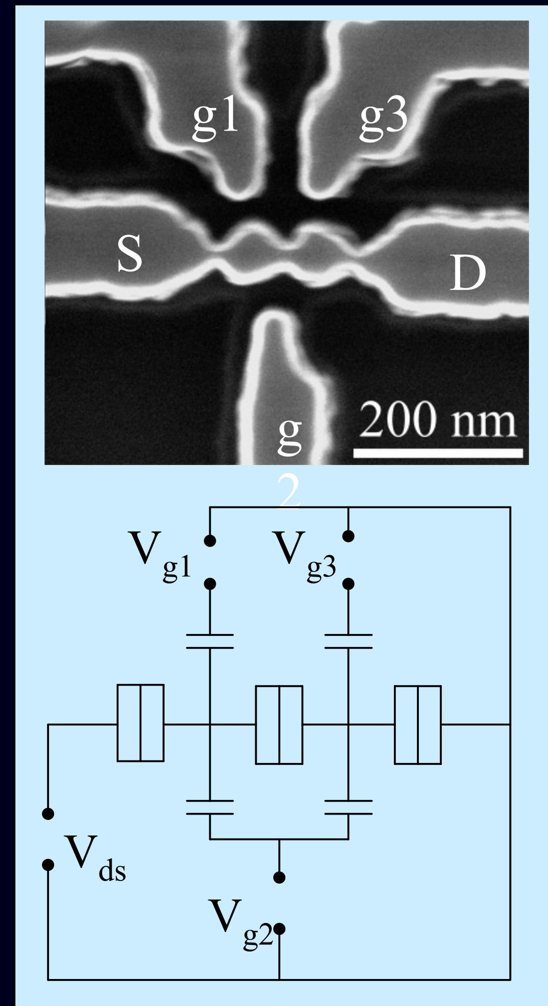
3. **Measurement**

   After the evolution, we need to interact with the system once more

Trench-isolated Silicon:Germanium



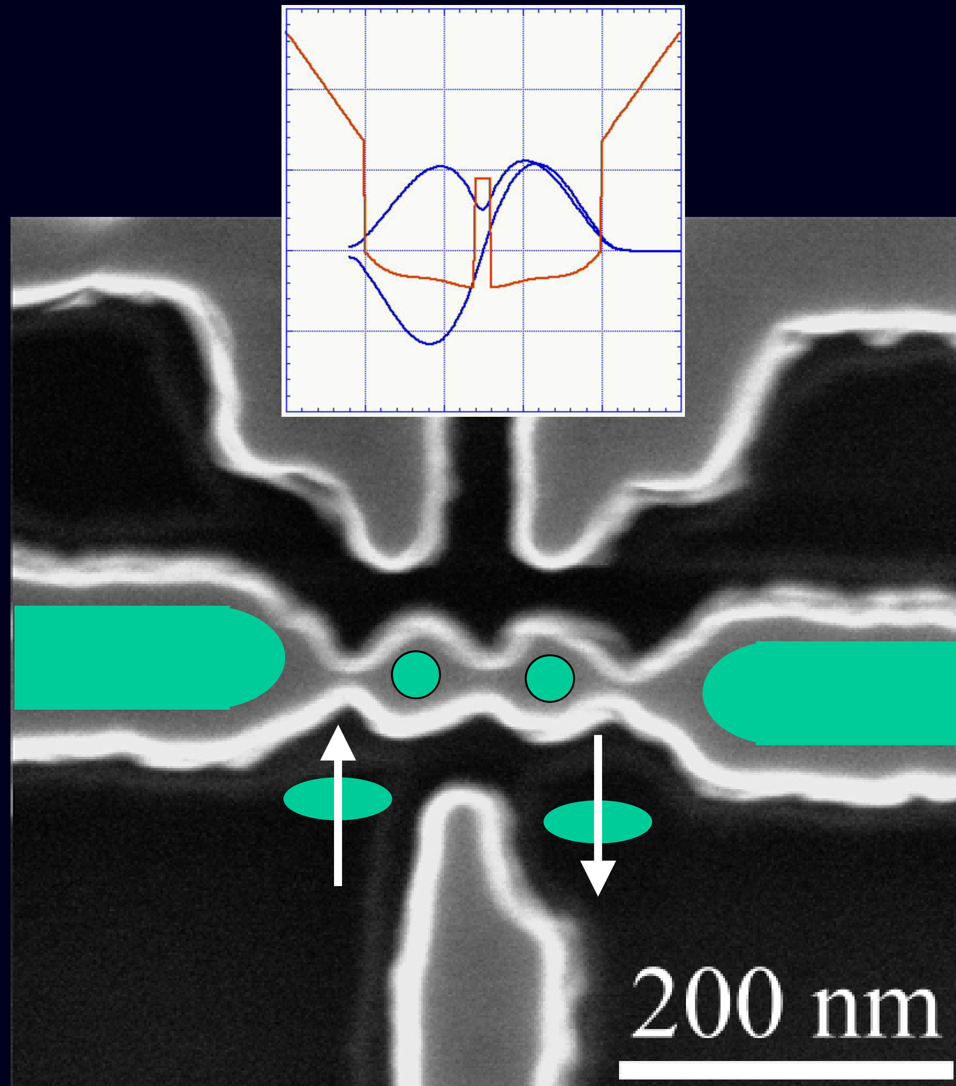
(Also plain silicon-on-insulator (SOI))



1. Gate - gate coupling is reduced
2. Two-dimensional structures are fabricable
   Metal gates can also be added
3. A hard-wall confining potential is obtainable

Charge and Spin Qubits

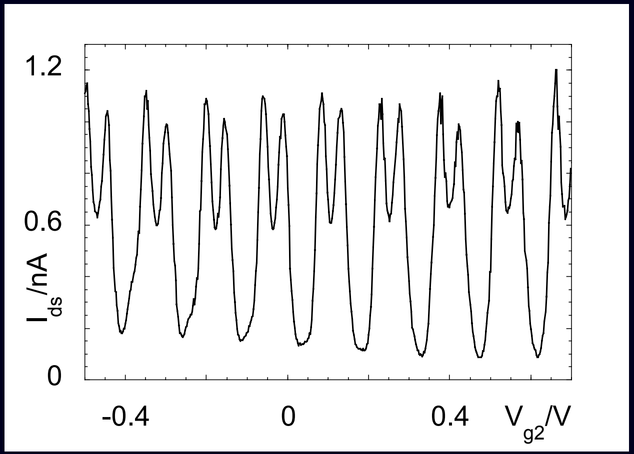
The double-dot system may be used as a single charge qubit or a double spin qubit

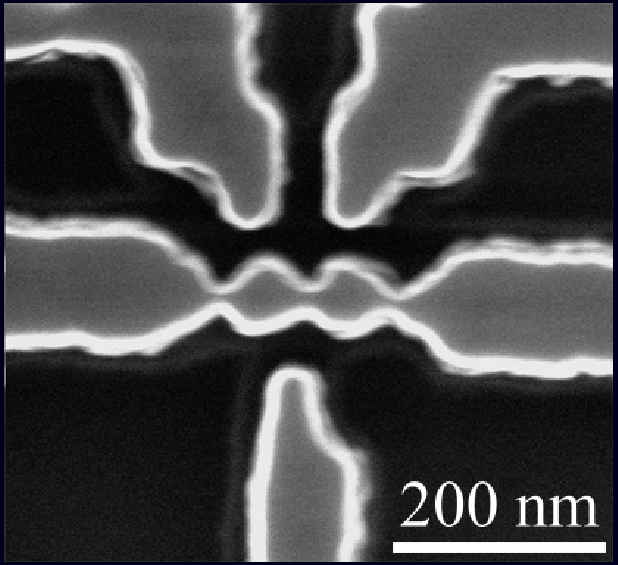


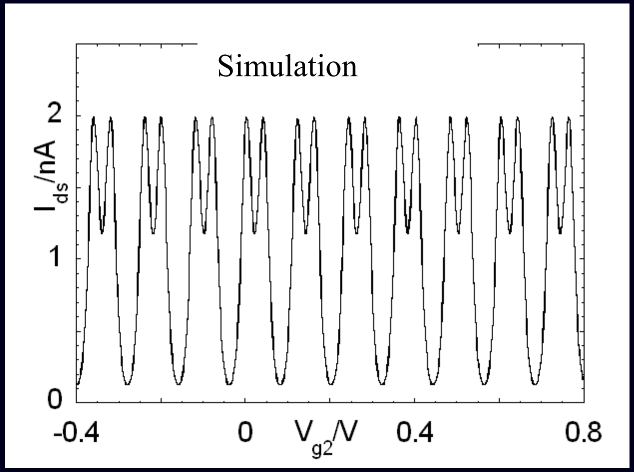
What is the true potential distribution at any time?

Observation of peak splitting

Peak splitting indicates that the presence of an extra charge on one one dot significantly affects the energy of the other dot. Overall period calculated from lithographic structure.



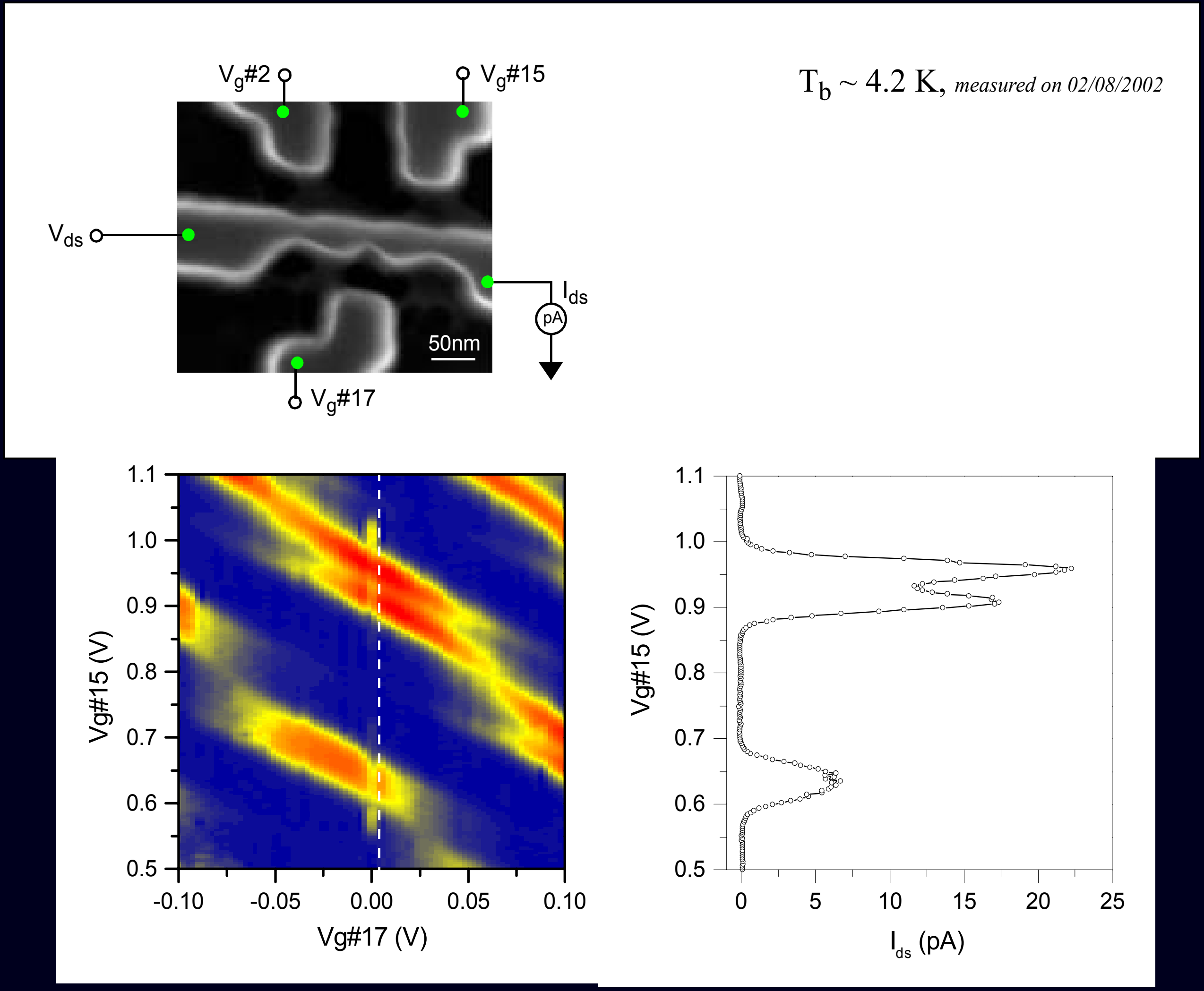




Effective dot size is 30nm - peak splitting is seen at 4.2K instead of previously at 50mK

Cain, Ahmed and Williams APL 78, 3624 (2001)

Molecular State @ 4.2K ?



Advantages of the structure for QC

1. State preparation

Suitable voltages applied to the contacts and gates can be used to prepare the dots in a known charge state.

2. Evolution without decoherence

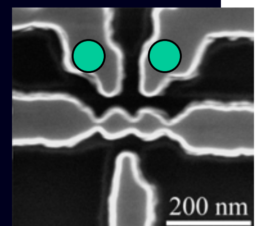
A combination of low temperatures and local energy filtering can be used to maintain coherence for a sufficient time.

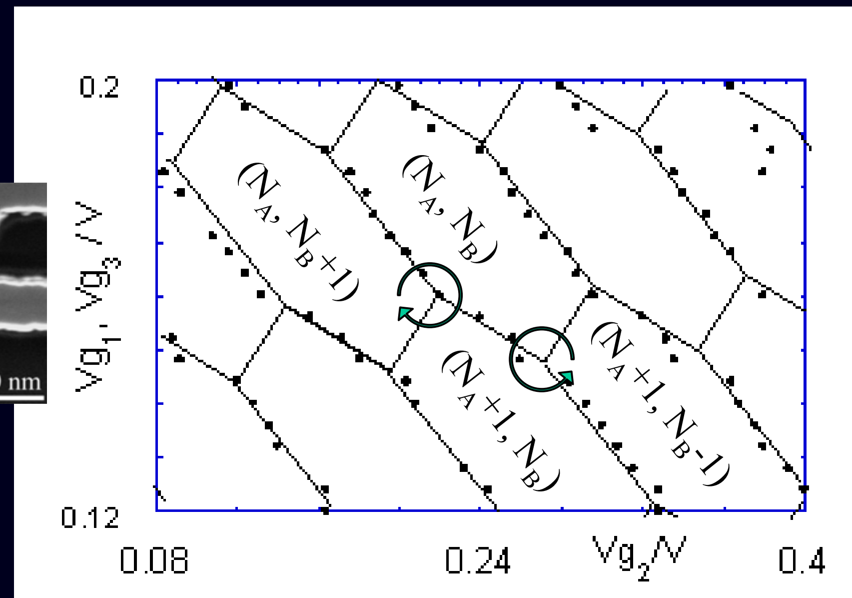
3. Measurement

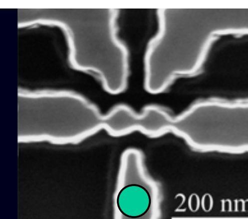
Highly sensitive single-electron electrometers can be integrated with the dots to perform both control and measurement.

Stability Diagram for Two p-Dots

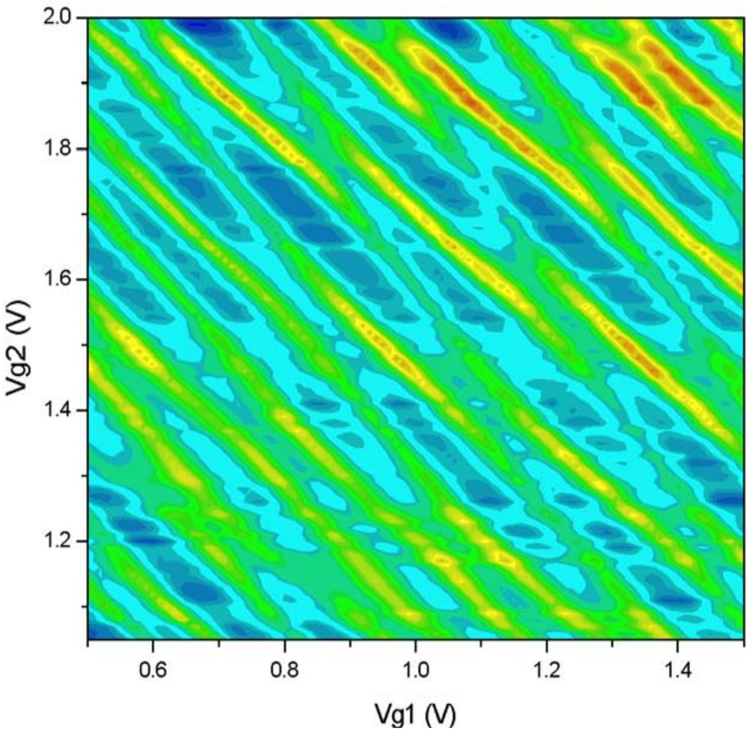
- Each region has a different charge state, e.g. (N_A, N_B)
- Crossing a boundary where the conductance maxima occur changes the charge state of one dot by ± 1
- Crossing a boundary where no maxima occur transfers a charge from one dot to the other only
- For sequential tunnelling, only expect resonances at the triple points.

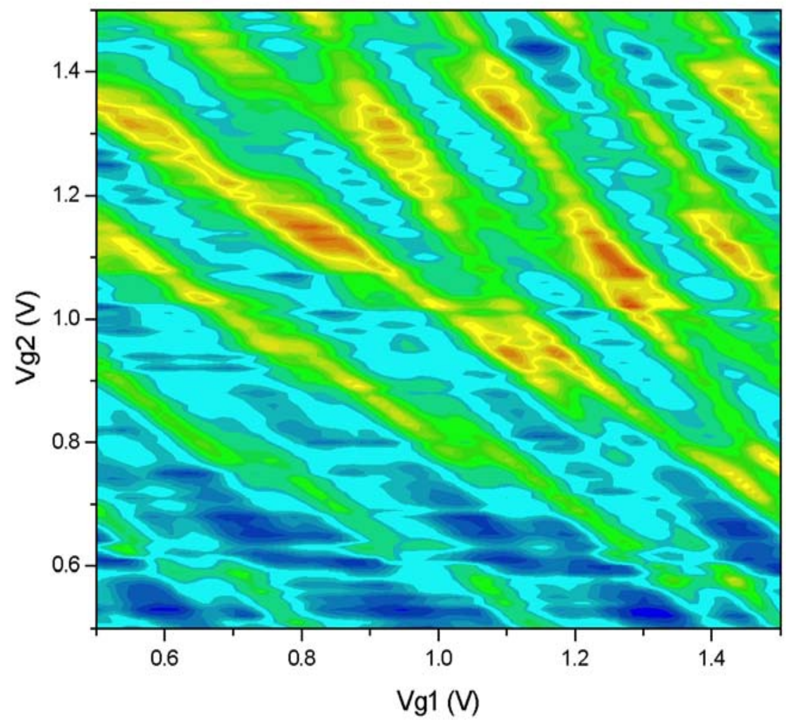


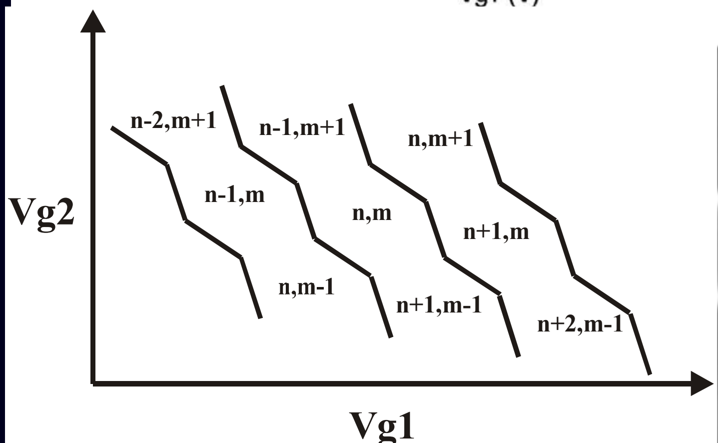


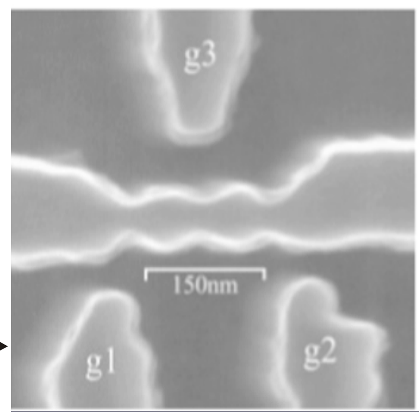


Control of double n-dot states









Strategies to Reduce Decoherence

1. Improved electromagnetic filtration

2. Decouple control and measurement processes

3. Operate on timescales very much faster than decohering processes

4. Operate in “decoherence-free subspaces”

2.

Measurements (and Theory) Needed

1. Drive the system to prove that it is an appropriate two-level system (eg Rabi oscillations)

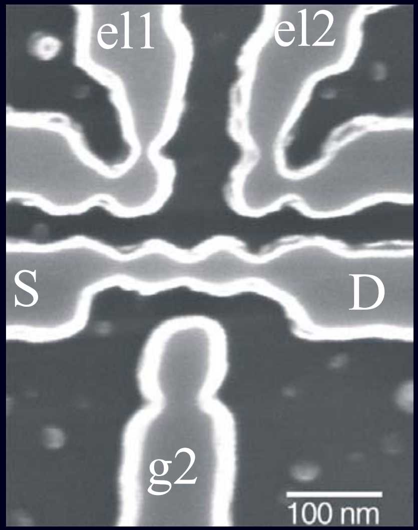
2. Demonstrate that a particular state can be set and maintained

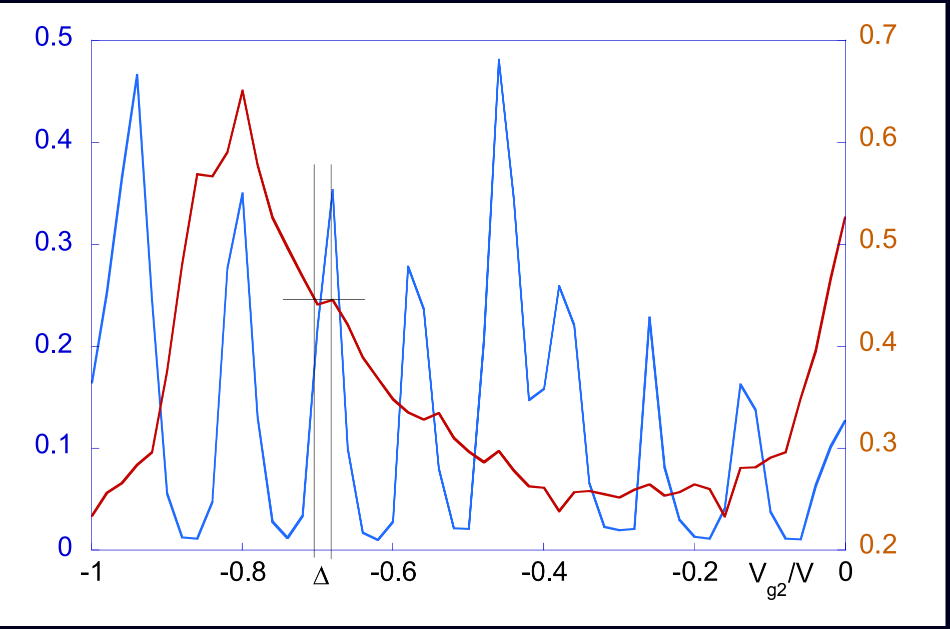
3. Demonstrate a single quantum gate

4. Show how to integrate gates

2.

Candidate For Charge Qubit



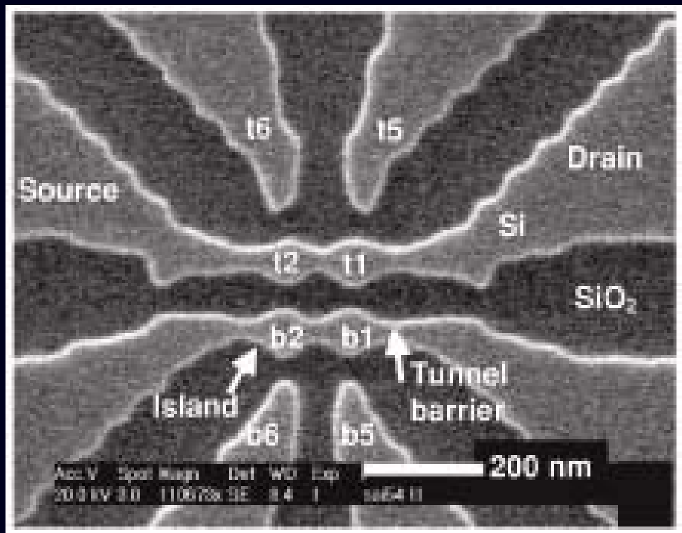


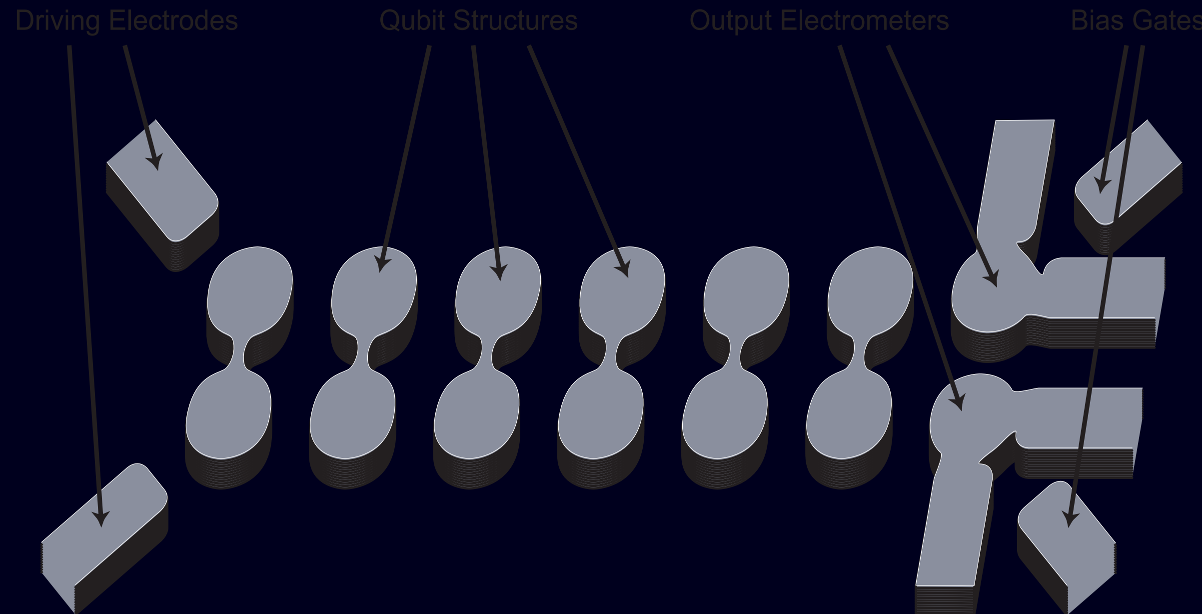
Electrometers are added which can be biased relative to the dots to perform both control and measurement

Cain, Williams and Ahmed

JAP 92, 346 July 2002

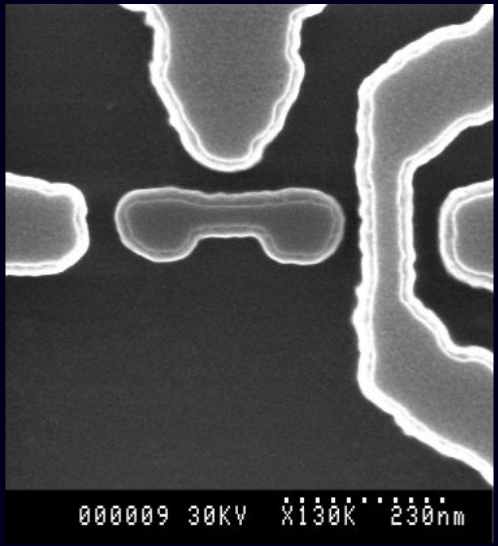
Scaling?



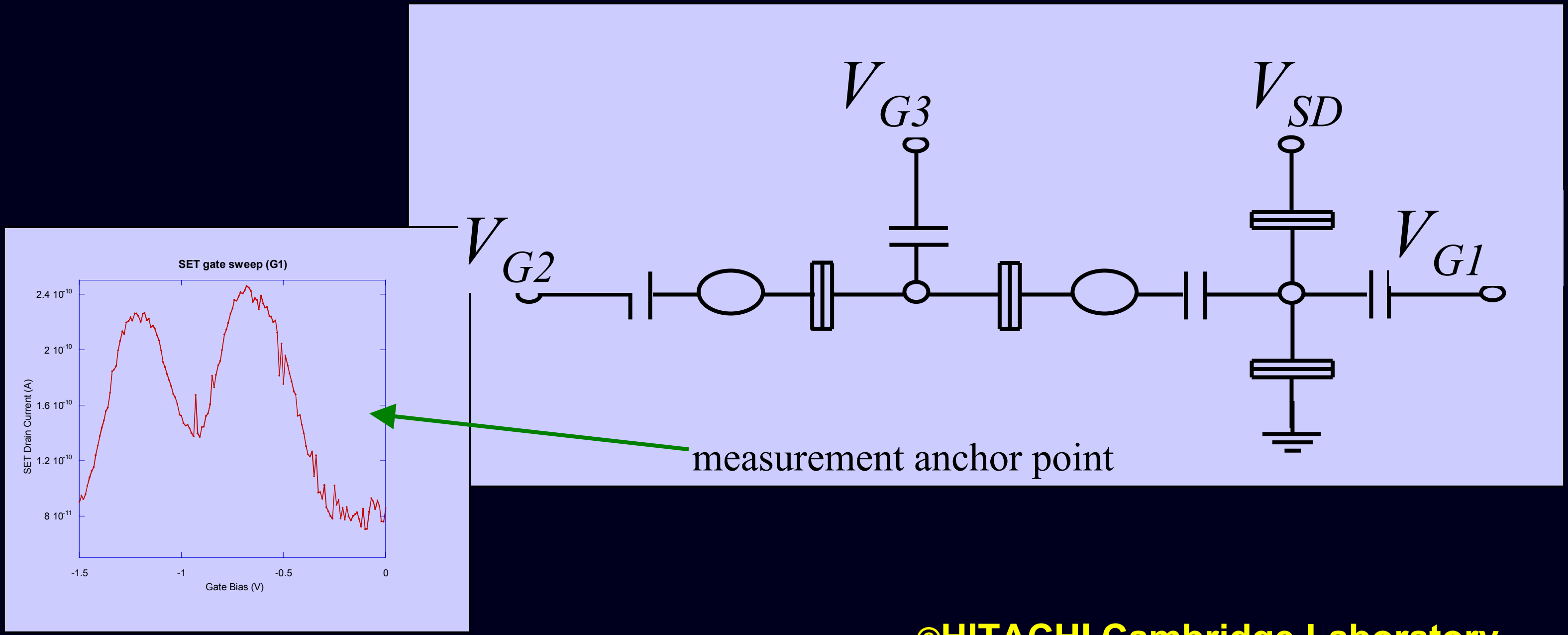


We need to integrate the qubits to make quantum gates, with controlled qubit-qubit interactions, state initialisation, control during processing, and readout.

Closed Double-Dot

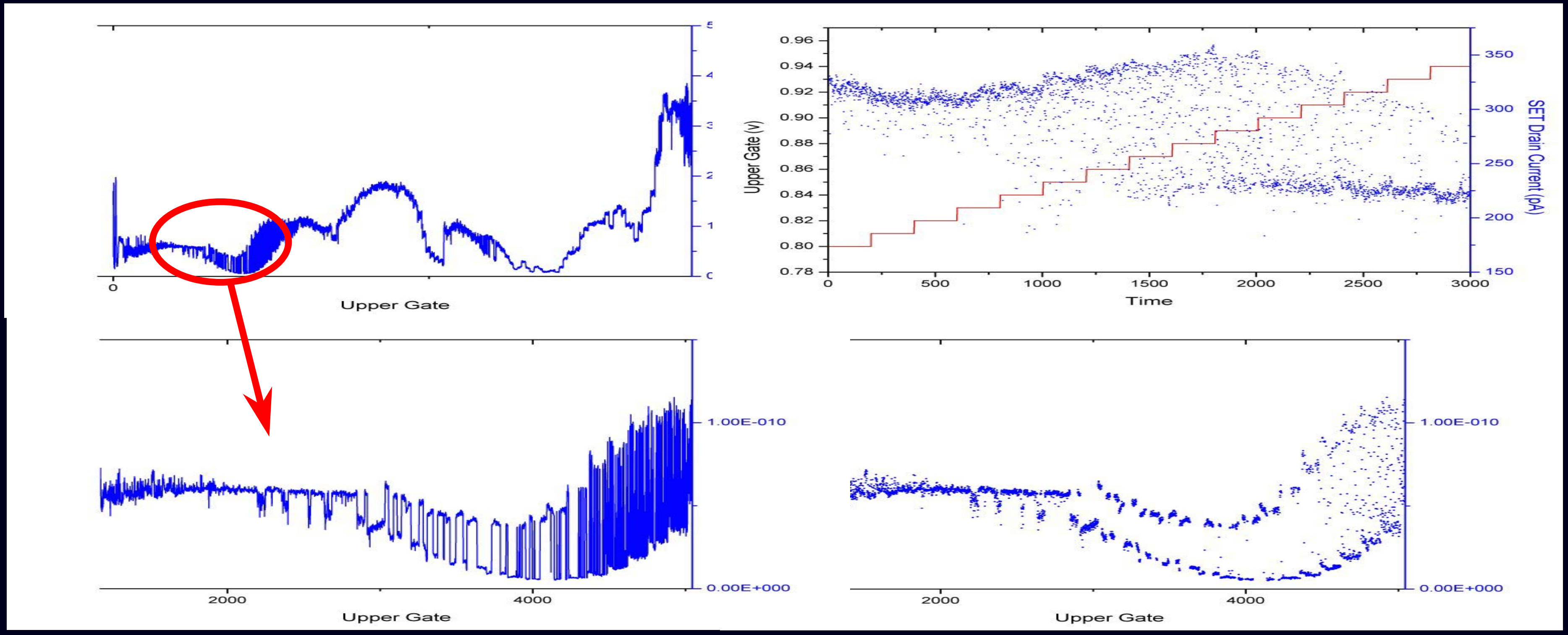


- Top-down approach
- Isolated, scalable charge-state system
- Manipulation and measurement through capacitive coupling
- SET current depends on parametron polarization
- Parametron polarization depends on gate voltages and previous history



Tuneable Switching

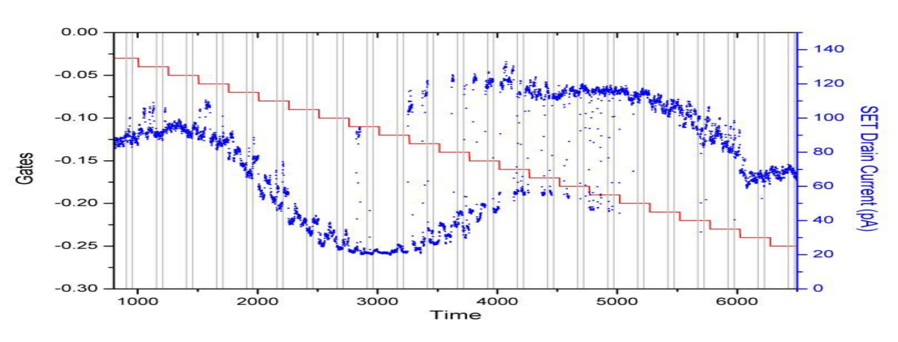
- Observe telegraph-type switching between two states characteristic of one electron
- Rate of switching depends very strongly on upper gate voltage (V_{G3}). Can continuously tune this rate from stable to higher than sensitivity of measurement apparatus

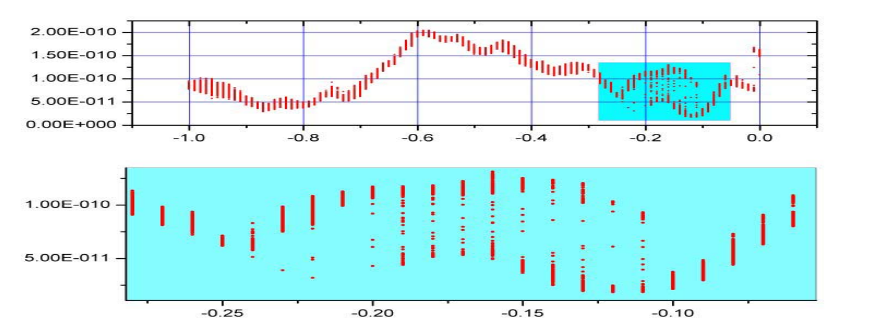


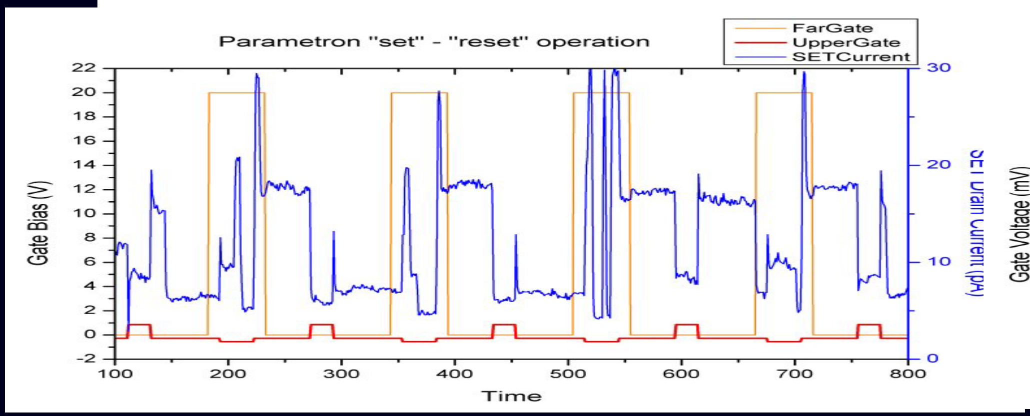
All measurements taken at 4.2K

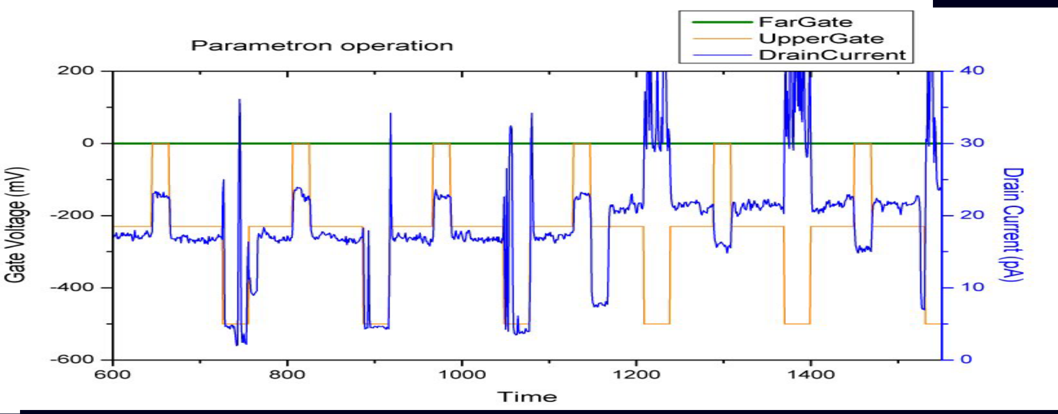
Manipulation using pulses

- Set-Reset operation achieved by selection of appropriate pulse amplitudes and durations and time delay between far gate and upper gate pulses
- State-switch achieved through tuning upper gate pulse









All at 4.2K

Current Status

Nanoscale quantum dots and associated infrastructure can be fabricated using electron-beam lithography

We would like to know the potential landscape in more detail

The electron occupancy of an individual quantum dot or a set of quantum dots can be controlled

We need to get a detailed picture of the electron wavefunctions

Tunnel barriers can be lowered and raised as required to vary the interaction between dots

We need to know the molecular states, and prove they exist

The charge distribution is detectable with electrometers

But is this detection process switchable as required?

A device which integrates all of these effects can be used as a single qubit

But for this to be useful we have to integrate the qubits.

Conclusion

All the elements for a semiconductor qubit have been demonstrated independently and several have been integrated

Schemes exist for integrating the qubits for making quantum gates

A deeper theoretical understanding of the electron / hole transport behaviour in these systems is needed:

- Full dynamical 3-D Poisson solver
- Detailed theory of electron transport and decoherence
- How to measure / infer the behaviour of closed systems?
  - (Perform a quantum computation?)

There is much work still to do...

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Coherence and Scaleability

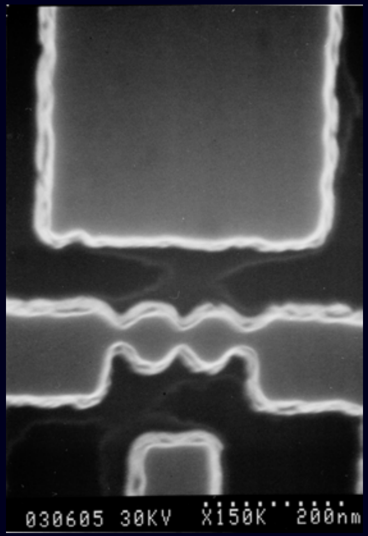
In principle, solid-state systems should offer the best chance of making a scaleable quantum computer

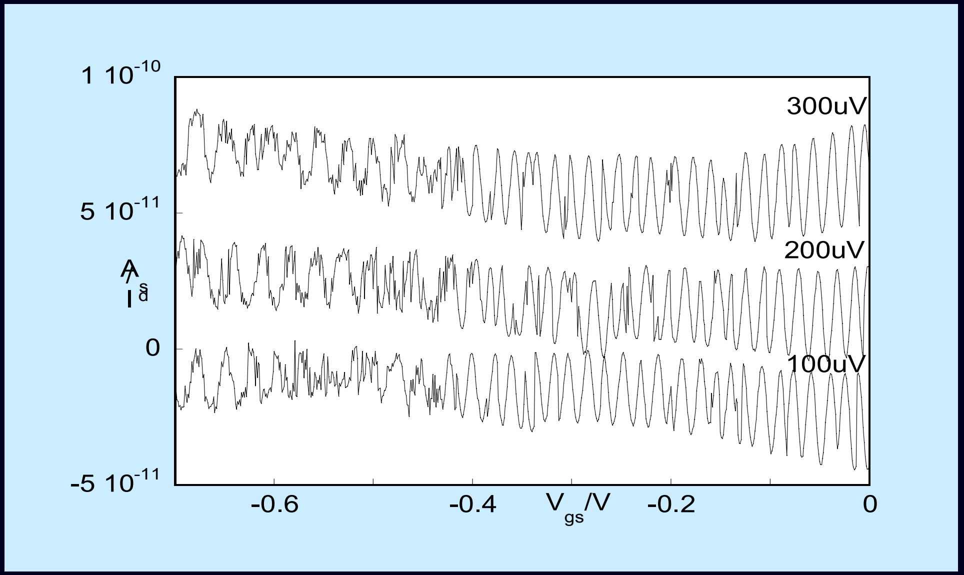
However, there are formidable problems ahead

Maintaining coherence for a time sufficient for computation is the largest problem for practical implementations - the very interactions which are useful for control, measurement and scaling provide routes for decoherence

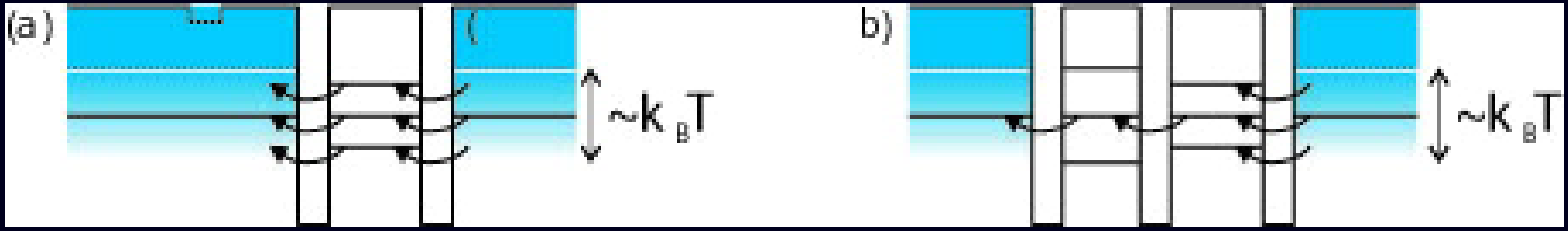
We also need to understand the various decohering processes and determine which are important in particular circumstances.

Towards control of coherence



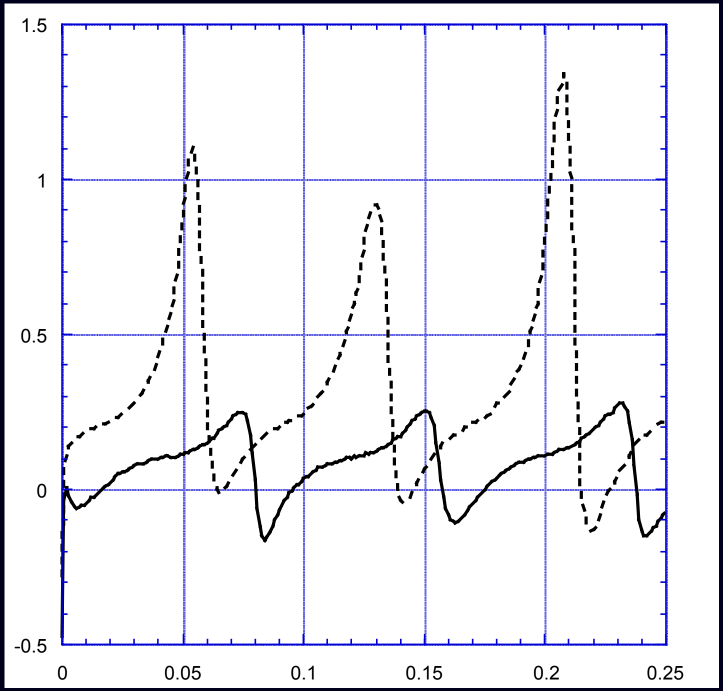


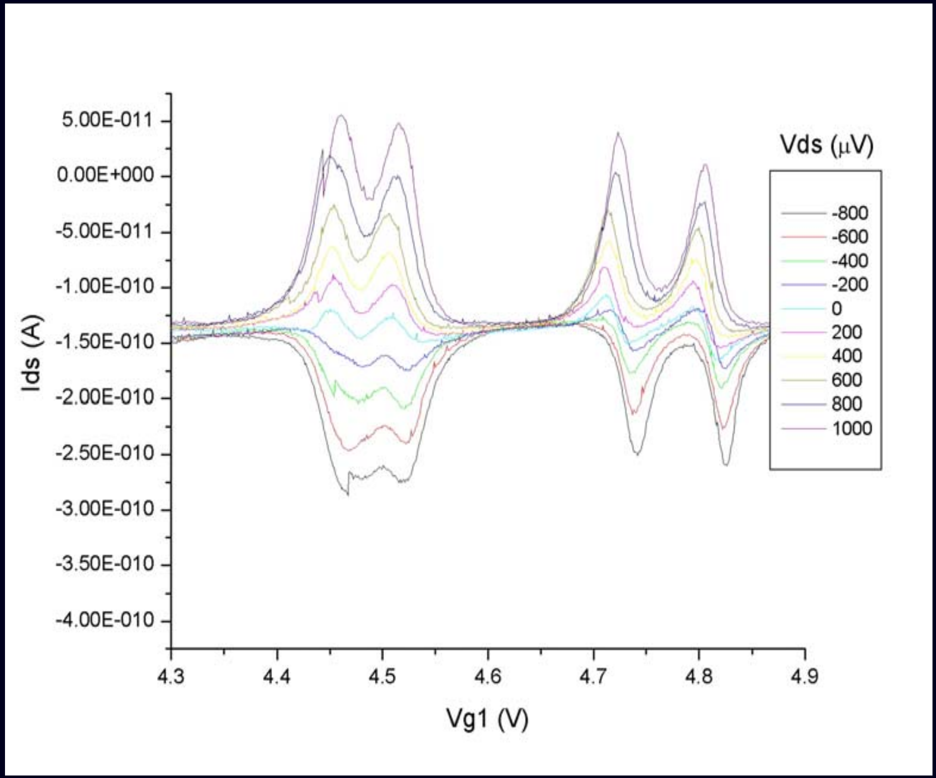
A gated double quantum dot made from a silicon - silicon germanium heterostructure. When the electronic structure changes from one dot to two in series, the noise is reduced.



Cain, Ahmed, Williams & Bonar APL 77, 3415 (2000)

Photon-assisted tunnelling





With no source-drain bias, at 20mK, currents are observed due to electron tunnelling driven by 4.2K black-body radiation