Semiconductor Structures for Quantum Information Processing

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Lancaster Nanoelectronics Meeting
07.01.03
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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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Coulomb Blockade Oscillations

Simulations using CAMSET
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

SiGe material

Intrinsic Si
p-type Si$_{0.9}$Ge$_{0.1}$
Intrinsic Si
SiO$_2$
Si Substrate

(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
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 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?

T_b ~ 4.2 K, measured on 02/08/2002

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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 \(\pm 1\)

• 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

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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”

Measurements (and Theory) Needed

1. Drive the system to prove that it is an appropriate two-level system (e.g., 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
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

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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

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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.