Solid State Approaches
to
Quantum Information Processing
and
Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.6

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List of Acronyms and Abbreviations

2-D	two dimensional
2-DEG	two-dimensional electron gas
C-NOT	controlled-NOT (gate)
CPB	Cooper pair box
CV	carbon vacancy
CW	continuous wave
ESR	electron-spin resonance
FET	field-effect transistors
GHz	gigahertz
GHZ	Greenberger, Horne, and Zeilinger
kHz	kilohertz
MHz	megahertz
mK	millikelvin
MRFM	magnetic resonance force microscope
NMR	nuclear magnetic resonance
NV	nitrogen vacancy
QC	quantum computation/computing
QD	quantum dot
QED	quantum electrodynamics
qNOT	quantum-NOT (gate)
rf	radio frequency
SAW	surface-acoustic wave
SET	single-electron tunneling
SPD	single-photon detector
SPS	single-photon source
SQUID	superconducting quantum interference device
STM	scanning-tunneling microscopy
T	Tesla
TEP	Technology Experts Panel

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Solid State detailed summary in the process of developing a roadmap for achieving quantum computation (QC). Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts Panel (TEP) member. With your input we can improve this roadmap as a guidance tool for the continued development of QC research.

Table 1-1
Approaches to Solid State QC Research

Research Leader(s)	Research Location	Research Focus
Awschalom, D.	UC-Santa Barbara	GaAs spin systems, excitonic systems
Barrett, S.	Yale	ESR in semiconductor devices
Clark, R.	U. of New South Wales	P in Si
Das Sarma, S.	Maryland	theory
Doolen, G.	LANL	theory
Ensslin, K.	ETH	GaAs quantum dots (QDs)/rings
Gammon, D.	NRL	single exciton spectroscopy
Hammel, P. C.	Ohio State U.	magnetic force spin readout
Hawley, M.	LANL	P in Si
Kane, B.	Maryland	P in Si
Kastner, M.	MIT	GaAs QDs (spin decoherence)
Kotthaus, J.	Munich	GaAs QDs
Kouwenhoven, L.	TU Delft	GaAs QDs
Levy, J.	Pitt	Si/Ge QDs
Loss, D.	U. of Basel	theory
Marcus, C.	Harvard	GaAs wires and dots, Carbon nanotubes
Nakamura, Y.	NEC	Cooper pair box (CPB)
Pepper, M.	Cambridge	surface-acoustic wave (SAW) channeled electrons, Na in Si
Raymer, M.	U. of Oregon	QDs in microcavities
Rossi, F.	Torino, Italy	theory
Roukes, M.	Caltech	high frequency and quantum cantilevers
Sachrajda, A.	NRC Ottawa	GaAs QDs, edge states
Schenkel, T.	LBNL	P in Si
Schoelkopf, R.	Yale	rf single-electron tunneling (SET) device and CPB
Schwab, K.	NSA	quantum cantilevers and CPB
Sham, L. J.	UC-Santa Barbara	theory
Steel, D.	U. of Michigan	excitons & trions in QDs
Tarucha, S.	Tokyo	GaAs QDs
Tucker, J.	U. of Illinois at Urbana-Champagne	P in Si

Table 1-1
Approaches to Solid State QC Research

Research Leader(s)	Research Location	Research Focus
	U. of Wisconsin consortium	Si/Ge QDs
Webb, R.	Maryland	GaAs QDs
Whaley, B.	UC-Berkeley	theory
Yablonovich, E.	UC-Los Angeles	P in Si

2.0 Background and Perspectives

The work of recent years, starting in the mid 1990s, has uncovered a very large number of possible solid-state systems in which quantum computing might be achieved, reflecting the huge variety of quantum phenomena that are known in condensed matter physics. Given the current state of discussions and progress on these proposals, it is the judgment of the TEP that the most important existing progress in the laboratory, and the clearest prospects for continuing mid-term progress, is provided by localized "spin" or "charge" qubits, which will be described here in detail. We do not exclude the possibility that further progress on various of the other proposals, including electrons on liquid helium, quantum Hall edge states, carbon tubes and balls, semiconductor nanowires, or others might make them worthy of detailed assessment at a later date.

Many of the variations on the spin and charge approaches discussed here rely on the fact that in many solid state systems, the spin states of localized electrons or of nuclei, form well-defined, highly coherent two-level systems that are useable as qubits. The quantum-gate implementations typically rely on the most natural physical interaction between spins, the exchange interaction. It is envisioned that a highly miniaturizable, all-electronic or optoelectronic qubit is conceivable in this area. Localized spins are available via confinement to QDs or impurity atoms, by entrainment by SAW techniques, and by other methods. While the necessary device-fabrication techniques for QDs are available down to single-electron spins, this is not the case yet for impurity atoms. QDs are a versatile system for qubits; other schemes, including excitonic qubits with optical addressing and coupling, have been devised as well as optically driven spin based QDs using a charged exciton as an optically induced transient high-speed gate. Quantum mechanical systems, using nanocantilevers, can also play a role in coupling and reading out solid-state qubits.

In a system using optically driven quantum-dot excitons, charge refers to the fact that the state of the qubit is determined by the state of excitation of an electron-hole pair in a semiconductor QD. In this case, the qubit becomes the optical Bloch vector where a $|0\rangle$corresponds to the optical Bloch vector pointing down $|\downarrow\rangle$and the dot is unexcited. Excitation of the dot leading to formation of the exciton now puts the qubit value at $|1\rangle$and the optical Bloch vector pointing up $|\uparrow\rangle$. The decoherence time in this system is then limited by the optical dipole, which determines the radiative recombination rate. Measurements have shown there are generally no other dephasing mechanisms. The clock-speed is limited by the reciprocal pulsewidth that would excite higher lying states of the dot. This leads to a limiting figure of merit probably near or somewhat in excess of 10^3. QDs are produced either epitaxially or by chemical synthesis. Two-qubit nonscalable devices can be demonstrated in single QDs using orthogonally polarized excitonic transitions. The interactions between the two qubits essential to creating entanglement are produced by higher-order Coulomb coupling leading to bi-exciton formation. Scalable systems have been envisioned where nearby QDs interact via dipole-dipole coupling, wave-function overlap, or radiation coupling via an optical cavity. The relatively fast decoherence, determined by radiative lifetime, is often seen as a limiting liability in these systems. However, these systems represent the prototypical optical excitation needed to enable optical manipulation of single-electron spins for spin-based qubit. Interestingly, the exciton QD is a charged-based system where the dot is neutral. In most cases of interest, the spin-based qubit in a QD is charged. The optical excitation path uses the same path as in the exciton system, but a second photon is needed to complete the rotation of the spin.

The basic ideas that are being pursued in this area were laid out by Loss and DiVincenzo (QDs) [1], and were adapted to impurity spins by Kane [2], and extended to optically driven spin-based systems by Rossi and Zoller [3] and Sham *et al.* [4]. Two specific examples in solid-state systems are impurity spins and spins in QDs [1].

2.1 Nuclear spin of P donors in Si

The nuclear spin ($I = 1/2$) of ^{31}P is a natural two-level system embedded in a spin-free substrate of ^{28}Si ($I = 0$). The nuclear spins of ^{31}P donors are separated by approximately 20 nm and there is a hyperfine interaction between donor electron spin and nuclear spin (qubit). Interaction between qubits is mediated through the donor-electron exchange interaction. The spins are maintained at millikelvin (mK) temperatures in an external magnetic field of several Tesla, perpendicular to the plane of the substrate. Nanoscale surface A and J gates control the hyperfine and exchange interactions at qubit sites. Two distinct states have been observed in ensemble nuclear magnetic resonance (NMR) experiments, but not in single-spin systems. Radio frequency (rf) coils can be used to apply π-pulses (or surface control gates can be pulsed in the presence of a continuous wave [CW] rf field B_{ac}), demonstrated in ensemble-spin systems but not single-spin systems. Rabi oscillations are yet to be demonstrated for single spins. The system scales essentially linearly with respect to resources (gates, donors, etc).

2.2 Electron spin in GaAs QDs

The spin of a single electron confined in a QD provides a natural qubit which can be manipulated either electronically or optically. The QD can be defined by 50-nm-wide electrostatic gates on top of a AlGaAs/GaAs two-dimensional electron gas (2-DEG), or by three-dimensional (3-D) confinement in a patterned semiconductor heterostructure, with a center-to-center distance between dots of about 200 nm. It is currently possible to isolate a single electron in each of two such QDs. In equilibrium at 300 mK and 5 Tesla (T), the electrons will be in the ground state spin-up with > 99% probability. An essential idea of the proposal is an all-electrical control of spin via electrical gates, i.e., to make use of a ''spin-to-charge conversion'' based on the Pauli principle obeyed by electrons. The spin of the electron is used as storage of quantum information, while the charge and Coulomb interaction of the electron allows for fast gate operations and readout. In addition, if the magnetic field is oriented perpendicular to the substrate, the leads provide a reservoir of spin-polarized electrons, which can serve as a reference for qubit readout. Pulsed microwave fields on resonance with the spins give single-qubit rotations, and electrostatic control of the exchange interaction between spins in neighboring dots permits two-qubit gates. Both types of quantum gates still need to be demonstrated. The resources (gates etc.) scale linearly with the number of qubits.

An all-optical approach allows us to exploit the advances in ultrafast laser technology, potentially integrated on-chip without the use of metallic gates and electrical coupling. QDs can be defined by 3-D confinement in a patterned semiconductor heterostructure, with a center-to-center distance between dots of about 200 nm. QDs can be doped with a single electron and operated at 4K at magnetic fields of order 7–10 T. Quantum logic-gate operations involving spins of single electrons confined in QDs occur through the exchange interaction of spin to nearby QDs through the spin-spin interaction. The gate interaction is controlled by an ultrafast solid-state laser which transiently excite electron-hole pairs (excitons or trions) that mediate the spin-spin interaction.

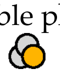
3.0 Summary of Solid-State QC: The DiVincenzo Criteria

Note: For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a)  = a potentially viable approach has achieved sufficient proof of principle;

b)  = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c)  = no viable approach is known.

1. A scalable physical system with well-characterized qubits (gated or optically driven spins). 

   In the solid state, a number of candidate qubits may be characterized by the following groupings:

   - spins in confined structures such as
     - laterally or vertically coupled lithographic QDs,
     - spins confined in a two-dimensional (2-D) system,
     - doped colloidal QDs,
     - high-spin magnetic nanoparticles,
     - nuclear-spin lattices or ensembles,
     - nuclear-spin heterolayers, and
     - single-electron-doped self-assembled or patterned QDs or single electrons in SAW channels;
   - *impurity spins* such as
     - shallow donors in Si, SiGe, or GaAs;
     - paramagnetic ions in C_{60};

  - paramagnetic ions in carbon nanotubes; and
  - nitrogen vacancy (NV) diamond centers or rare-earth color centers;
- *charged or excitonic systems* **(**the numbers indicate an quantum-dot-exciton-based qubit system is scalable based on any of the three coupling schemes using adjacent QDs; the single-quantum-dot system is not significantly scalable beyond two qubits**)** such as
  - electron position in double quantum wells,
  - helicity of excitons trapped at a III-V heterostructure interface,
  - electrons in quantum wires, and
  - localized Cooper pairs in quantum wires; and
- *mechanical systems* such as the phonon states of high Q nanocantilevers.

For each candidate qubit, characterization involves the demonstration of coherent oscillations, between the two states, whether accurate π-pulses can be applied and if the qubit system is scaleable.

2. The ability to initialize the state of the qubits to a simple fiducial state (gated or optically driven spins).

The important measures of the success of initialization include how well the qubits can be initialized, how quickly they can be reset, how long the initialization takes, and what has been demonstrated to date.

- *Spin systems:*
  - electron spins require cryogenic temperatures (<4K) and
  - nuclear spins require special techniques (such as the Overhauser effect), dynamic nuclear polarization or optical pumping, or techniques for manipulating individual spins using electric fields or magnetic-field gradients. A promising approach currently under study is the use of optical pulse shaping for state initialization.
- *Charge systems* require the use of external voltages applied to gates to control the electron position.
- *Excitonic systems* require laser excitation of specific helicity.
  - This system is easily initialized. It relaxes to the $|0\rangle$ state within 50 ps to 1 ns, depending on the dot structure. It may be driven to the $|1\rangle$ state with an optical π-pulse.
- *Mechanical systems* require the cooling of cantilevers to reduce the degrees of freedom. Pumping techniques have been proposed.

3. Long (relative) decoherence times, much longer than the gate-operation time (gated or optically driven spins).

For each proposal, several mechanisms of decoherence exist. In the case of QD excitons, extensive measurements have been performed at the single-dot level and ensemble level that show coherence times ranging from 50 ps to 1 ns, depending on dot size and is due to radiative decay rather than pure dephasing. A few measurements have been performed for individual qubits to date. However some low-temperature ensemble measurements exist as detailed below. All the times quoted here should be measured against gate times that are hoped to be on the order of 1 ns.

- *Spins in confined structures:* Ensemble measurements for electrons in GaAs, T_2 ~1 μs (at least).
- *Impurity spins:* Ensemble measurements of electron T_2 for P in Si ~1 ms.
- *Charge or excitonic systems:* Electron spatial coherence times (~1 ns in GaAs QDs) generically less than spin coherence time. Exciton coherence times typically 10s of ps to ns but can be greatly lengthened by electron-hole separation.
    - The minimum switching time is determined by energy spacing to adjacent states, which at present is believed to be around 1 ps or perhaps somewhat smaller. More studies are needed to know these numbers more accurately.
- *Mechanical systems:* No available data.

4. A universal set of quantum gates (gated or optically driven spins).

Solid-state implementations use a variety of techniques to perform arbitrary rotations of single qubits together with two-qubit coupling to perform all universal gate operations. Techniques used for single-qubit operations include:

- *spins in confined structures QDs:*
    - Heisenberg operations alone,
    - local magnetic fields,
    - ESR rotation of spins,
    - Rabi driven trion (optical Raman) transitions (with/without cavities/photonic bandgap),
    - magnetic-field gradients with rf pulses,
    - displacement of electron wave function into high-g regions,
    - Rashba and spin-orbit modulation using gate modulation of electric fields, and
    - ac Stark effects [5];
- *impurity spins:*
    - Stark, Knight, Zeeman, or lande-g-factor shifted electron and nuclear resonances using surface gates;
    - local magnetic fields and rf fields; and
    - optical resonance techniques including laser excited Raman transitions; and
- *charged or excitonic systems* (the universal gates in this system is comprised of controlled-NOTs and single-qubit rotations or other possible gates, such as phase gates):
    - stark shifts are controlled by optical fields,
    - resonant microwave or optical fields,
    - Raman excitation, and

- gateable or fixed dipole-dipole interaction.

4.1 Two-qubit operations

Physical implementations of two-qubit operations are more uniform across the different systems, and are generally performed via the Heisenberg-exchange interaction (RKKY for optically driven doped QDs) or dipole-dipole coupling for some cases of nuclear spins. Electrostatic control of a barrier between two qubits manipulates the exchange coupling. Cavity quantum electrodynamics (QED) or optical-dipole coupling is also being explored for systems such as carbon vacancy (CV)-diamond.

5. A qubit-specific measurement capability (gated or optically driven spins).

To operate a quantum computer, it is necessary to be able to read out the state of a specific qubit with high accuracy (high probability). In some sense, qubit (single spin) measurements have been accomplished already quite some time ago; the Moerner and Orrit groups in 1993, independently, measured single spins using optical techniques. But for the solid-state qubits under consideration, workable techniques are not yet in place; a number of different strategies are being pursued to achieve this goal:

- *Spins in confined structures:* A number of techniques have been proposed for readout:
  - Conceptually, the simplest approach is to perform direct readout of the spin using a spin-filter such as a magnetic semiconductor.
  - An elegant suggestion (Loss-DiVincenzo) is to convert the spin information to charge information through a spin-dependent tunnelling process, and then detect the resultant spin-dependent charge transfer using highly sensitive electrometers such as submicron field-effect transistors (FETs), quantum point contacts, or SETs.
  - Optically driven resonance fluorescence (analogous to optically cycling in ion traps) and cavity-enhanced (QED) absorption are promising techniques for dots with optical transitions available.
  - A further promising suggestion is to read out the spin on the dot via a transport current (spin-polarized) passing through the QD. Due to Pauli blocking, the current is typically 10–1000 times larger for spin up than it is for spin down [6].
  - Mechanical methods of detecting the spin/charge state of the qubit have also been proposed, based on magnetic resonance force microscope (MRFM) techniques would be applicable independent of optical or transport properties.
  - Nanomagnetometers such as nano-SQUIDs (superconducting quantum interference devices) have also been suggested, as well as solid-state Stern-Gerlach devices.
  - Near-field optical readout has also been proposed, using luminescence or Faraday rotation. Progress toward this goal was reported in *Science* by Guest *et al.* [7].

- *Impurity spins:* The readout techniques for this architecture are essentially the same as for spins in confined structures:
  - For nuclear-spin devices the information stored on nuclear spins can be transferred to the associated donor-electron spin through the hyperfine interaction. The electron spins can then be detected through the methods outlined above.
- *Charged or excitonic systems:* In these systems readout is either optical or electrostatic:
  - Optical techniques include luminescence readout and ensemble optical readout.
  - Electrostatic techniques include SET readout and for the specific case of e/He, state-selective tunnelling of electrons from the liquid He surface.
  - More work is needed in this area, but it is envisioned that optically driven qubits must be within a few hundred angstroms of each other in order to have adequate coupling. This is well below the far-field spatial-resolution limit. One architecture that has been proposed uses an array of near-field optical-fiber probes to address specific qubits. An alterative approach is to use coherent control techniques to manipulate and read out specific bits. Another approach to readout is to use electrical methods. Optical-readout proposals are limited at present except for the generally accepted approach of signal averaging.
- *Mechanical systems* such as the phonon states of high-Q nanocantilevers.
  - Proposed approaches to detection of the cantilever's displacement include SET detection of electrostatic interaction or heterodyne optical measurements.

6. The ability to interconvert stationary and flying qubits.

This would allow different parts of the quantum computer to be connected at will, and act as a bus. This requires movement of the individual qubits throughout the device. Interesting progress toward to this end has come from another scientific area called coherent optical control [8].

- *Spins in confined structures and impurity spins:* Flying qubits are possible for some of these architectures and could consist of mobile electrons guided through the host material by surface gates or channels in the material or photons confined to optical waveguides.
- *Charged/excitonic systems:* There has been relatively little work in this area. Optical-cavity coupling and fiber-optical interconnects have been mentioned, but this area remains open for further investigation.
- *Mechanical systems:* No flying qubits are envisioned for these systems.

7. The ability to faithfully transmit flying qubits between specified locations.

The ability to convert qubits stored at specific points in the computer into flying qubits will be advantageous for scale-up and error correction. The question, then, is how to transfer the information stored on a fixed qubit to a flying qubit:

- *Spins in confined structures and impurity spins:* As mentioned above, flying qubits have not been extensively investigated for these systems. Conversion between fixed and mobile qubits could involve exchange interaction between electrons bound at a donor site and free electrons, electrons tunnelling into quantum wires, or coupling to photons via microcavities with single-photon sources (SPSs) and detectors (SPDs). Indeed, in the case of optically driven qubits, the fact that spins in GaAs QDs are optically active with the application of a magnetic field can be exploited for the transfer of the spin qubit to a flying photonic qubit, using cavity-QED techniques to achieve the needed high fidelity.

- *Charged/excitonic systems:* As indicated in item 6, relatively little effort has been given to this problem.
- *Mechanical systems:* No ideas for flying qubits have been considered at this time.

4.0 What Has Been Accomplished

At present, only a few of the metrics below have been partially achieved within the solid-state arena. As examples, single-qubit action, in an ensemble setting, is well documented in recent Awschalom work and earlier spin-resonance work. Steel and coworkers have evidence for entanglement of electron-hole states in a single QD as well as Rabi oscillations corresponding to qubit rotations. However, the plan of the coming years' effort is taking shape, and a reasonable view can be given of how these metrics will be approached.

At present, the solid-state community, and much of the quantum-information community, is correctly focused on Rabi flops and relatively simple quantum logic operations. While this is important, it is likely that several technologies will have sufficient coherence for QC. It is important to realize however that the decisive issues for assessing the promise of a technology for a scaleable QC will come after coherence has been demonstrated. It will then be necessary to learn how to control quantum information flow between devices. It is clear that some technologies will have significant advantages over others. For example, nearest-neighbor-only coupling will have disadvantages compared to schemes where quantum information can be communicated over long distances. Two- (or three-) dimensional arrangements of quantum logic devices will be superior to approaches in which devices are arranged linearly.

The solid-state approaches should show their strengths when the following considerations start to become important:

- fast qubits will be better than slow qubits,
- parallel is better than serial, and
- small qubits will be better than big qubits.

All of these points seem obvious, but precisely the opposite conditions apply for doing early easy experiments. Slow qubits are easier to control with precision than fast ones. Big qubits are easier to fabricate than small ones. (Note that 'easier' here is relative, as there are no easy experiments in quantum information science and technology.)

4.1 All of the above bode well for solid-state approaches

With regard to solid-state implementations, systems in which, for example, electrons convey information will be advantageously fast due to the small electron mass. Similarly, whilst approaches centered on electrons in solids require the 'hard' fabrication of architectures such as quantum-dot and single-donor-atom arrays on the nanometer or atomic scale, they avoid many obstacles to scaling such as cross talk between electromagnetic fields of macroscopic circuits which are more easily fabricated with conventional technology.

The specific case of spin qubits is a good example, as this particular solid-state implementation has features that make it extremely well positioned to overcome the obstacles to scaling and it has properties favorable for all of the criteria mentioned above. The dominant spin interactions are local and can be very fast. Spins on electrons can be transported rapidly. Because the dominant interaction between them falls off exponentially with distance, large amounts of quantum information can be transported with minimal amounts of unwanted interaction. Parallel operations and 2-D architectures are realizable in principle.

4.2 A long-term view

Whilst experiments on solid-state qubits are difficult, and particularly hard for spin, it is important to emphasize that the ‘easy’ qubits are not necessarily the best qubits for a large-scale quantum computer and that ‘difficult’ nanostructured qubits in solids have highly favorable properties necessary for large-scale quantum computer architectures, despite the tremendous challenges facing this research.

4.3 Metrics and Milestones: Gated Qubits

Note: For the status of the metrics of QC described in this section, the symbols used have the following meanings:

a)  = sufficient experimental demonstration;

b)  = preliminary experimental demonstration, but further experimental work is required; and

c)  = no experimental demonstration.

1. Creation of a qubit
   1.1 Demonstrate preparation and readout of both qubit states. 

2. Single-qubit operations
   2.1 Demonstrate Rabi flops of a qubit. 
   2.2 Demonstrate decoherence times much longer than Rabi oscillation period. 
   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere. 

3. Two-qubit operations
   3.1 Implement coherent two-qubit quantum logic operations. 
   3.2 Produce and characterize Bell states. 
   3.3 Demonstrate decoherence times much longer than two-qubit gate times. 

4. Operations on 3–10 physical qubits
   4.1 Produce a Greenberger, Horne, & Zeilinger (GHZ)-state of three physical qubits. 

4.2 Produce maximally entangled states of four and more physical qubits.

4.3 Quantum state and process tomography.

4.4 Demonstrate decoherence-free subspaces.

4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits.

4.6 Demonstrate quantum error-correcting codes.

4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).

4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit

   5.1 Create a single logical qubit and "keep it alive" using repetitive error correction.

   5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits

   6.1 Implement two-logical-qubit operations.

   6.2 Produce two-logical-qubit Bell states.

   6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–10 logical qubits

   7.1 Produce a GHZ-state of three logical qubits.

   7.2 Produce maximally entangled states of four and more logical qubits.

   7.3 Demonstrate the transfer of quantum information between logical qubits.

   7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.

   7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

4.4 Metrics and Milestones: Optically Measured QD Qubits

1. Creation of a qubit

   1.1 Demonstrate preparation and readout of both qubit states.

2. Single-qubit operations

   2.1 Demonstrate Rabi flops of a qubit.

   2.2 Demonstrate decoherence times much longer than Rabi oscillation period.

   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

3. Two-qubit operations

   3.1 Implement coherent two-qubit quantum logic operations.

   3.2 Produce and characterize Bell states.

   3.3 Demonstrate decoherence times much longer than two-qubit gate times.

   3.4 Demonstrate quantum state and process tomography for two qubits.

3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).

3.6 Demonstrate a two-qubit quantum algorithm.

4. Operations on 3–10 physical qubits

4.1 Produce a GHZ-state of three physical qubits.

4.2 Produce maximally entangled states of four and more physical qubits.

4.3 Quantum state and process tomography.

4.4 Demonstrate decoherence-free subspaces.

4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits.

4.6 Demonstrate quantum error-correcting codes.

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6.2 Produce two-logical-qubit Bell states.

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7. Operations on 3–10 logical qubits

7.1 Produce a GHZ-state of three logical qubits.

7.2 Produce maximally entangled states of four and more logical qubits.

7.3 Demonstrate the transfer of quantum information between logical qubits.

7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.

7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

4.5 Metrics and Milestones: Doped or “Spin” QD Qubits

1. Creation of a qubit

1.1 Demonstrate preparation and readout of both qubit states.

2. Single-qubit operations

2.1 Demonstrate Rabi flops of a qubit.

2.2 Demonstrate decoherence times much longer than Rabi oscillation period.

2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

3. Two-qubit operations
    3.1 Implement coherent two-qubit quantum logic operations.
    3.2 Produce and characterize Bell states.
    3.3 Demonstrate decoherence times much longer than two-qubit gate times.

4. Operations on 3–10 physical qubits
    4.1 Produce a GHZ-state of three physical qubits.
    4.2 Produce maximally entangled states of four and more physical qubits.
    4.3 Quantum state and process tomography.
    4.4 Demonstrate decoherence-free subspaces.
    4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits.
    4.6 Demonstrate quantum error-correcting codes.
    4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).
    4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit
    5.1 Create a single logical qubit and “keep it alive” using repetitive error correction.
    5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits
    6.1 Implement two-logical-qubit operations.
    6.2 Produce two-logical-qubit Bell states.
    6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–10 logical qubits
    7.1 Produce a GHZ-state of three logical qubits.
    7.2 Produce maximally entangled states of four and more logical qubits.
    7.3 Demonstrate the transfer of quantum information between logical qubits.
    7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.
    7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

5.0 Considerations

1. Special strengths
   - 1.1 Semiconductor systems (GaAs, Si, SiGe,) offer inherent scalability. Established and new semiconductor patterning processes allow for the construction of submicron 2-D arrays of qubits.
   - 1.2 Semiconductor systems have compatibility with existing microelectronics industry and have high potential for development of integrated on-chip devices.
   - 1.3 Spin qubits in semiconductors are well-defined "native" qubits (two-level systems).
   - 1.4 Spin qubits in semiconductors (single donor or QDs) can be decoupled from charge fluctuations, leading to long decoherence times (from s to ms) compared with practical gate operation times (from ps to ns).
   - 1.5 Charge qubits in semiconductors (e.g., electron position in double quantum wells) offer potential for extremely fast qubit (ps) operations. Single-charge detection has been demonstrated with SETs.
   - 1.6 There is the potential for coupling to flying qubits (e.g., in QDs attached to quantum wires, see reference [9]).

2. Unknowns, weaknesses
   - 2.1 Background impurity levels and disorder in semiconductor systems may lead to difficulties in device reproducibility. These issues are common with sub-100-nm devices in conventional microprocessors.
   - 2.2 For spin qubits—single-spin readout has not been demonstrated and will be challenging. Best technique still to be determined from electrical (SET); optical; or mechanical (MRFM).
   - 2.3 For spin qubits—actual decoherence times for stationary *single* electron/nuclear spins not yet measured. Measurements will require single-spin readout. Further theoretical calculations are also needed.
   - 2.4 For spin qubits in Si—the exchange interaction is predicted to oscillate as a function of donor separation, which may place stringent requirements on nanofabrication accuracy.
   - 2.5 For charge qubits—decoherence likely to be dominated by voltage fluctuations on control gates and may be fast. Experiments on GaAs dots indicate dephasing times on the order of ns.
   - 2.6 Most semiconductor-based schemes are based on linear qubit arrays. The extension to 2-D arrays will require via-gate techniques on the sub-100-nm scale, which is challenging.
   - 2.7 A number of solid-state schemes are still at the conceptual phase. Detailed fabrication strategies still to be developed.

3. Goals 2002–2007
   - 3.1 Readout
     - 3.1.1 *Spin qubits:* single-spin measurement demonstrated as a general capability

3.1.1.1 Spin-selective charge displacement/tunneling transport induced by electric or electromagnetic fields followed rf-SET readout or cavity-QED readout.

3.1.1.2 Direct magnetic measurement of single spin by force detection with an MRFM employing high Q nanocantilevers; this approach should be distinguished from optical or transport approaches in that it is a general approach whose applicability is independent of optical or transport properties of the material or the presence of gates.

3.1.1.3 Advanced development of other possible readout schemes:

- solid-state Stern-Gerlach device,
- near-field optical readout—luminescence, Faraday rotation,
- ESR-STM detection of Larmor precession in STM tunneling current, and
- optical-readout via spin coupling to singly addressable sites (e.g., NV center in diamond).

3.1.2 *Charge, Excitonic, and Mechanical systems:* measurement capability in place

- SET readout,
- luminescence readout,
- ensemble optical readout, and
- heterodyne optical measurement of cantilever displacements.

3.2 Qubits and quantum gates

3.2.1 *Spins in confined structures:*

- few-qubit entanglement in Loss-DiVincenzo scheme has been demonstrated,
- good scientific understanding of sources of decoherence and precision issues,
- reliable fabrication process and materials issues addresses,
- plan for scaling to 10+ entangled qubits, and
- convergence with impurity schemes.

3.2.1.1 Possible:

- demonstrate reliable quantum gates in a few-qubit array.

3.2.2 *Impurity spins:*

- few-device version of Kane scheme has been largely realized,
- strong but not perfect quantum measurements have been demonstrated,
- reliable fabrication process and materials issues have been addressed, and
- we have a plan for scaling to 10+ entangled qubits.

3.2.2.1 Possible:

- develop hybrid conventional—quantum processor architectures in Si for few-qubit arrays, including some convergence with on-chip, ultra-fast superconducting circuitry, or HEMT GaAs circuitry (for compatibility with high magnetic fields).
- demonstrate a functioning linear array of dopant qubits in Si structure, with reliable measurements achieved.

3.2.3 *Charge/Excitonic Systems:*

- controllable entanglement of charge qubits and of excitons demonstrated and
- potential of extremely fast qubit operations evaluated.

3.2.3.1 Possible:

- simple device with several qubits demonstrated and
- potential of coupling to flying qubits demonstrated.

4. Goals 2007–2012

4.1 Resolve all major physics and materials-science issues.

4.2 Develop fast control and readout schemes.

4.3 Develop process tomography for gates, algorithms, and decoherence.

4.4 Demonstrate fault-tolerant gates and decoherence-free subspaces.

4.5 Demonstrate 10 or more entangled qubits.

4.6 Plan for scaling to 100 or more entangled qubits.

4.7 Converge on best type of solid-state qubit.

4.8 Demonstrate coupling to flying qubits.

4.9 Achieve advances in reducing required precision for a reliable quantum computer.

Possible:

4.10 Develop a small-scale hybrid conventional/quantum processor for commercial applications.

5. Necessary achievements

5.1 Solve materials-fabrication issues in several schemes for electron-spin confinement.

5.2 Achieve good control of the reproducibility of these structures; suppress 1/f noise.

5.3 Develop precision high-speed instrumentation, perhaps involving on-chip electronics, for the all-electrical control of qubits.

5.4 Demonstrate a high-efficiency spin readout compatible with the qubit gate devices.

6. Trophies

6.1 *Demonstration of efficient generally applicable single qubit readout of spin state*. For example, for spin systems, the ability to detect a single electron or nuclear spin is a major physical challenge and would be a significant achievement in its own right. A readout technology independent of specific material or device properties will have broad impact as a tool for quantum device applications.

6.2 *Fabrication of devices with precise arrays of addressable qubits:* (e.g., creation of periodic dopant arrays in semiconductors with atomic precision; fabrication of large arrays of quantum wires for SAW channels).

6.3 Demonstration and characterization of single-qubit operations.

6.4 Creation and manipulation of entanglement between many subsystems.

6.5 Identification and demonstration of flying-qubit schemes.

6.6 Identification and demonstration of efficient error-correcting codes for qubits with nearest-neighbour interactions only.

6.7 QC with standard electronic control or all optical control.

7. Connections with other quantum information science technologies

7.1 NMR pulse-shaping techniques should be adapted to achieve precision control.

7.2 The potential for optical control and readout must stay on the table.

7.3 Continuing interaction with materials science and magnetics is necessary.

7.4 Strong links to research in classical spin-based electronics should be exploited.

8. Subsidiary developments

8.1 Nanofabrication challenges for semiconductor systems (particularly Si) are common to many of those for next generation of ultra large scale integration (ULSI) microprocessor chips, leading to synergies with developments in existing industry. Such challenges include precision donor placement, relevant to both a quantum computer and sub-100-nm transistors.

8.2 Solid-state QC systems require advanced bottom-up assembly approaches which are relevant to the broad new range of nanotechnology-based industries, such as those utilizing scanned-probe single-atom manipulation, carbon nanotube and C_{60} structures, and self-assembly of devices.

8.3 Many of the device capabilities needed for semiconductor-based QC have potential applications in the microelectronics industry, such as ultrafast (GHz) gating techniques and SET development.

8.4 Demonstrated optoelectronic semiconductor devices (lasers/photodetectors) offer hope for integration between on-chip quantum processing and fiber-based quantum communication.

8.5 Exiton-based QC systems have potential spin-offs in development of new optoelectronic systems.

8.6 Electronics exploiting quantum devices will have important impact on information-processing applications other than computing.

9. Role of theory

9.1 *For spin qubits:* Measurement of decoherence times will require single-spin readout. Considerable further theoretical calculations are needed; this includes decoherence by the lattice (phonons), decoherence due to voltage fluctuations on control gates and readout devices, and decoherence by impurity spins and charges. Many of these calculations are currently underway.

9.2 Calculation of decoherence induced by measurement back-action processes (SETs, MRFM, etc).

9.3 *For spin qubits:* Calculation of qubit coupling strengths for Si-, SiGe-, and GaAs-based schemes using real Bloch wave functions.

9.4 *For spin qubits:* We will need development of both general and specific strategies for achieving very accurate unitary control, including pulse shaping (for both optical and electrical pulses), refocusing, and unwinding of undesired evolutions.

9.5 Development of detailed measurement schemes (SET-, optical-, conductivity-based) to determine degree of entanglement.

9.6 Development of error-correction codes for specific architectures.

9.7 *For excitonic systems:* Determination of optical pulse shaping and understanding of exciton line widths.

9.8 *For mechanical systems:* Understanding of cantilever damping mechanisms.

6.0 Timeline

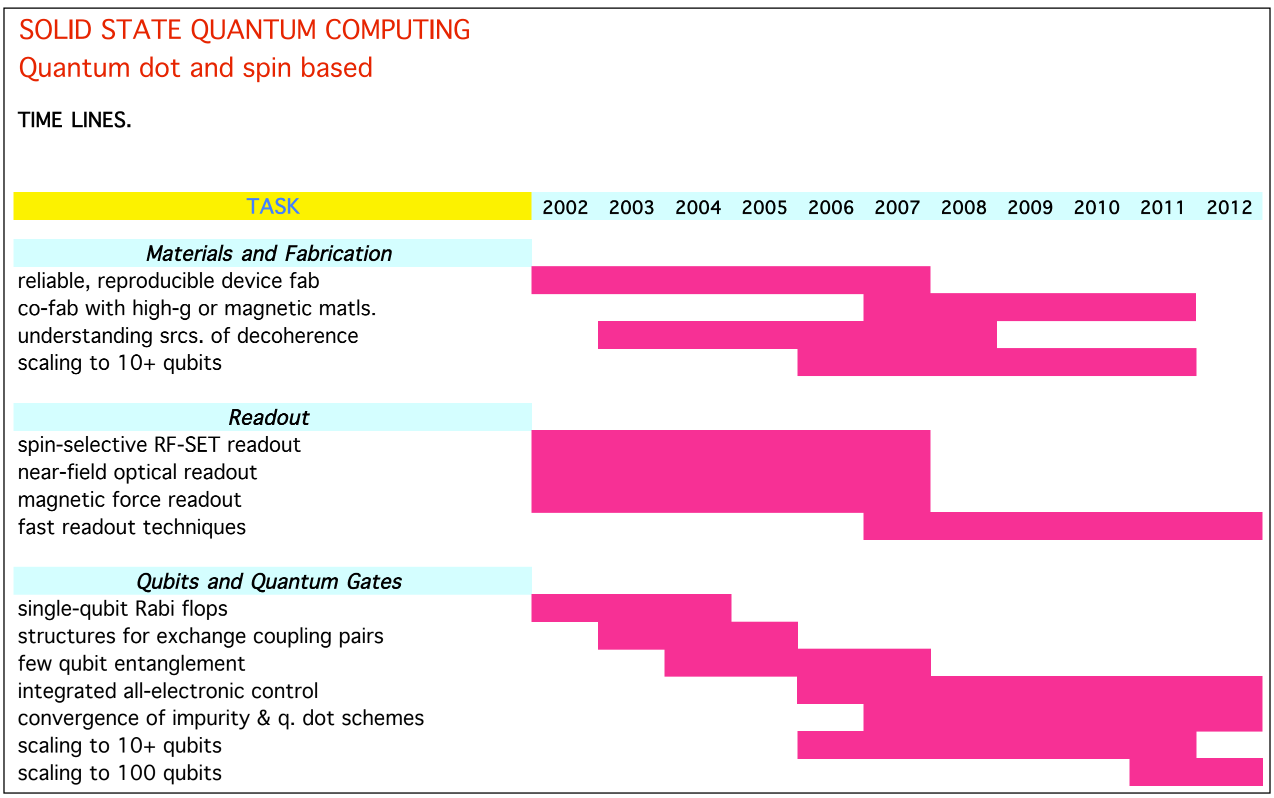

Figure 6-1. Solid state QC developmental timeline

1. Timeline for 2002–2007
   1.1 *Materials and Fabrication:* In the early years, the basic precise, reproducible fabrication of a number of important qubit structures will be done. As these devices are produced, a basic understanding of the origins and nature of decoherence in these structures will be obtained.
   1.2 *Readout:* Techniques for measuring single spins must be mastered in the early years. As time goes on, it should be learned how to make these measurements faster. Ultimately transduction to electrical signals will be important, but in the short term direct optical or mechanical readout will also be important.
   1.3 *Qubits and Quantum Gates:* Present progress on achieving single-spin Rabi flopping will continue. Within a couple of years realistic structures for exchange-coupling two spins should be built. Subsequent to that, few-qubit entanglement should be demonstrated.

2. Timeline for 2007–2012
   1.1 *Materials and Fabrication:* Hybrid structures should begin to emerge in which elements of spintronic, magnetic, and semiconducting structures are put together for optimized functionality. Feasible scalability to the 10 or more qubit level should be moving ahead.
   1.2 *Readout:* Methods of very fast, reliable, and fully parallel measurement should be achieved.
   1.3 *Qubits and Quantum Gates:* Integrated, all-electronic control of quantum gating should be achieved. Optimization of the impurity-based and QD-based qubits schemes, incorporating elements of both, should be achieved. Some simple problems involving 10 qubits should be attacked, and plans for scaling to larger systems should be in place.

7.0 Glossary

Quantum dot.
A confining structure for electrons, which can be designed to stably hold a small number of electrons.

Exchange coupling.
Basic physical interaction between the spins of electrons whose wave functions overlap, arising from the Pauli exclusion principle.

8.0 References

[1] Loss, D. and D.P. DiVincenzo, “Quantum computation with quantum dots,” *Physical Review A* **57**, 120–126 (1998).

[2] Kane, B.E.,“A silicon-based nuclear spin quantum computer,” *Nature* **393**, 133–137 (1998).

[3] Pazy, E., E. Biolatti, T. Calarco, I. D'Amico, P. Zanardi F. Rossi, and P. Zoller "Spin-based optical quantum gates via Pauli blocking in semiconductor quantum dots," (19-Sep-2001) preprint *cond-mat/0109337*.

[4] Piermarocchi, C., P. Chen, L.J. Sham, and D.G. Steel, "Optical RKKY interaction between charged semiconductor quantum dots," *Physical Review Letters* 89, 167402 (2002).

[5] Gupta, J.A., R. Knobel, N. Samarth, and D.D. Awschalom, "Ultrafast manipulation of electron spin coherence," *Science* **292**, 2458–2461 (2001).

[6] Recher, P., E.V. Sukhorukov, and D. Loss, "Quantum dot as spin filter and spin memory," *Physical Review Letters* **85**, 1962–1965 (2000).

[7] Guest, J.R., T.H. Stievater, G. Chen, E.A. Tabak, B.G. Orr, D.G. Steel, D. Gammon, and D.S. Katzer, "Near-field coherent spectroscopy and microscopy of a quantum dot system," *Science* **293**, 2224–2227 (2001).

[8] Stevens, M.J., A.L. Smirl, R.D.R. Bhat, J.E. Sipe, and H.M. van Driel, "Coherent control of an optically injected ballistic spin-polarized current in bulk GaAs," *Journal of Applied Physics* **91**, 4382–4386 (2002).

[9] Kane, B.E., "Silicon-based quantum computation," *Progress of Physics* **48**, 1023–1041 (2000).