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REVIEW OPEN

Engineering the quantum-classical interface of solid-state qubits

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Spanning a range of hardware platforms, the building-blocks of quantum processors are today sufficiently advanced to begin work on scaling-up these systems into complex quantum machines. A key subsystem of all quantum machinery is the interface between the isolated qubits that encode quantum information and the classical control and readout technology needed to operate them. As few-qubit devices are combined to construct larger, fault-tolerant quantum systems in the near future, the quantum-classical interface will pose new challenges that increasingly require approaches from the engineering disciplines in combination with continued fundamental advances in physics, materials and mathematics. This review describes the subsystems comprising the quantum-classical interface from the viewpoint of an engineer, experimental physicist or student wanting to enter the field of solid-state quantum information technology. The fundamental signalling operations of readout and control are reviewed for a variety of qubit platforms, including spin systems, superconducting implementations and future devices based on topological degrees-of-freedom. New engineering opportunities for technology development at the boundary between qubits and their control hardware are identified, transversing electronics to cryogenics.

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INTRODUCTION

In comparison to the physics that governs the operation of today's computers, quantum mechanics allows a different means of processing, storing and communicating information to enable powerful technologies not possible with classical logic. At present, a worldwide effort is underway to realise such technologies which exploit the unique physics and mathematics of the quantum world, namely, the superposition of quantised states of matter and light, entanglement and quantum measurement. Although our understanding of some of these phenomena already underpins much of modern technology, for example, in explaining the operation of transistors or lasers, it is only in the last decade or so that researchers have begun to experimentally realise solid-state devices that embed individual, yet fully controllable quantum systems. Qubit-platforms such as the spin orientation of individual electrons,[1] or even nuclei,[2–4] the location of a single electron charge,[5] quasiparticle[6,7] or Cooper pair[8,9] have become the building-blocks for constructing complex, synthetic quantum technologies from a variety of condensed matter systems. As these devices are scaled-up, operating them will require an autonomous means of controlling, interacting and reading out large numbers of qubits in parallel, a formidable task that will be met by combining new approaches from engineering disciplines with quantum science.

In what follows, the generic operating principles of quantum control, evolution and readout are introduced and reviewed from the point-of-view of the classical interface—the suite of hardware subsystems that serve as sensors and actuators of the physical quantum system (see Figure 1). These basic principles are then applied to the specific cases of semiconductor spin qubits, superconducting transmons and future topological devices, each of which may potentially underpin technologies that span general purpose quantum computers,[10] quantum simulators,[11] as well as new sensing[12] and metrology applications. Considering the scale-up of these quantum platforms, the development of new system-architectures, circuits, devices, materials and techniques comprising the quantum-classical interface are highlighted and reviewed from the perspective of the 'quantum engineer'—researchers with a working knowledge of quantum mechanics in combination with the engineering skill-set required to see this technology realised.

QUANTUM VERSE CLASSICAL SYSTEMS

Controlling and measuring quantum systems presents significant challenges in comparison to reading and writing classical information. At the core of these challenges is the phenomena of decoherence and quantum measurement, two related concepts that are central to the operation of all technologies exploiting individually controllable quantum systems. Measurement, or readout, allows information to be gained from a quantum system, but in accordance with the uncertainty principle, also disturbs it in proportion to the amount of information extracted.[13] Unlike in classical physics, quantum mechanics prevents the state of a qubit from being directly copied.[14] Alternatively, decoherence amounts to an unintentional measurement of the quantum system by its environment: the system is uncontrollably disturbed and the quantum information is lost (or, at best, locked-up in degrees-of-freedom that are inaccessible).[15]

Controlling quantum devices also requires approaches that go beyond the already vast repertoire of techniques developed for the optimal control of classical systems.[16] In many instances, new control techniques unique to the quantum domain are necessary to counter the effects of noise, either from the environment or control system itself, that would otherwise lead to decoherence

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and logic errors.[17] Unlike classical information processing with analogue signals, however, quantum systems can be made arbitrarily robust to noise, if this noise is below a certain threshold. Fault tolerance is achieved by employing the principles of quantum error correction,[18–20] a means of tracking and correcting errors, typically by encoding information redundantly across the system.[9,20,21]

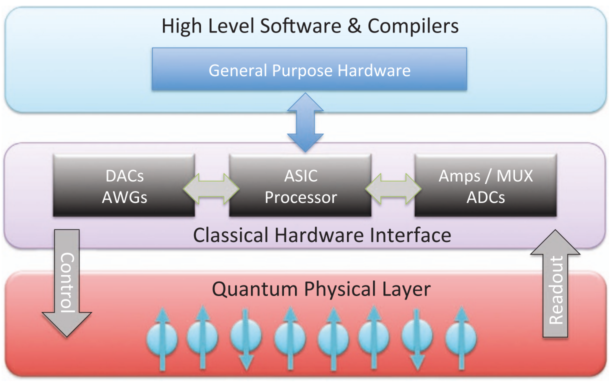

Figure 1. A possible configuration for the quantum-classical interface for controlling and reading out quantum technology. Information is passed to and from qubits in the quantum physical layer using classical circuits such as digital-to-analogue converters (DACs), arbitrary waveform generators (AWGs), analogue-to-digital converters (ADCs), amplifiers (Amps) and multiplexers (MUXs). Application-specific integrated circuits (ASICs) or field-programmable gate arrays (FPGAs) implement high-speed logic and feedback between readout and control. Quantum algorithms are compiled on general purpose processors and downloaded to the quantum-classical interface for execution.

SUPERPOSITION, EVOLUTION AND DECOHERENCE

For readers new to the topic, the experimental approaches underpinning magnetic resonance (MR) or similarly MR imaging, provide a useful introduction to controlling most solid-state quantum systems from an engineering perspective.[22] To illustrate the basic principles, a simplified MR control operation is shown schematically in Figure 2, where the arrow (pointing to the north pole of the Bloch sphere) represents the net magnetisation of an ensemble of nuclear spins in the presence of an external magnetic field. Although it is a macroscopic quantity, this spin magnetisation is directly analogous to the state vector of a qubit ψ and can be similarly manipulated to create complex superpositions of its ground $|g\rangle$ and excited $|e\rangle$ states with control pulses generated from external circuitry (see the caption of Figure 2 for details).

In the case of MR, an external magnetic field $\vec{B}_0$ creates an energy splitting between ground and excited states, setting the (Lamor) frequency at which the spin-magnetisation precesses, cyclically accumulating phase with time. The application of an ac magnetic control pulse, in resonance with the Lamor precession and perpendicular to $\vec{B}_0$, briefly alters the qubit energy causing it to evolve into a specifically chosen superposition of $|g\rangle$ and $|e\rangle$.[14] Variations in the energy splitting, due to fluctuations in the (magnetic) environment or noise in the control system, alter the precession frequency and thus phase acquired by the vector.[23] For ensembles of spins, such as in the case with conventional MR,

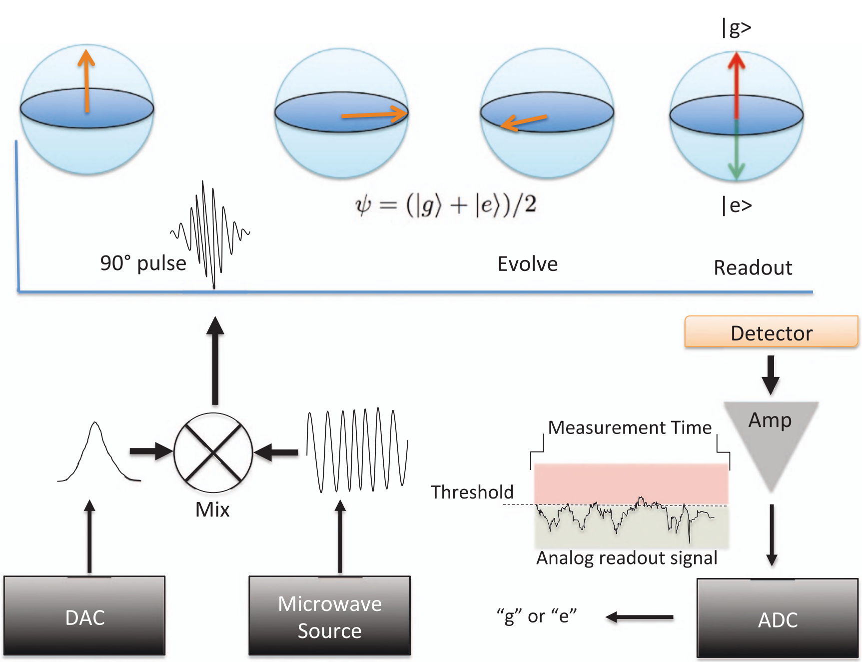

Figure 2. The experimental techniques employed in magnetic resonance (MR) are directly analogous to controlling quantum systems. To manipulate the angle of the state vector ψ, an oscillating magnetic field is applied perpendicular to the external field, and with a frequency that is nearly resonant with the precession frequency of the magnetisation. Simplistically, the perpendicular field acts on ψ with a force that is in resonance with its precession, rotating its angle on the Bloch sphere. The angle of ψ is then determined by the amplitude and time over which the oscillating field is applied in the form of a control pulse. Typically, such pulses are produced by modulating a microwave signal by an envelope pulse, for instance, a Gaussian waveform. In this set-up, the amplitude and the width of the Gaussian pulse directly determine the angle over which the state vector is rotated, shown in the figure as a 90° rotation, $\psi = (|g\rangle + |e\rangle)/2$ that yields an equal superposition of ground $|g\rangle$ and excited state $|e\rangle$. Corresponding unitary rotations are possible around all three axes of the Bloch sphere. The time scale for performing such single-qubit rotations is one aspect that limits the clock speed of a quantum computer. Today, single qubits can be rotated into arbitrary superpositions on timescales that range from sub-nanoseconds to microseconds.[9,56,83]

these variations lead to each spin acquiring a different phase after a time T_2^*, essentially averaging the collective coherent precession to zero. The same effect occurs for individual quantum systems when making ensembles of measurements on the same qubit again and again over a time scale in which the environment fluctuates.

If these fluctuations are slow relative to the precession frequency of the qubit, however, their effect can be nulled. This is done by reversing the direction of qubit precession mid-way through its evolution, allowing the qubit to rephrase after precessing in the opposite direction. The net effect of the reversal being that the total phase accumulated is zero. Such 'open-loop' control techniques[17,24,25] can extend the coherence time (labelled T_2), and are now in widespread use, particularly for controlling semiconductor qubits that are dephased by environmental noise that is non-Markovian, having a coloured frequency spectrum (e.g., $\sim 1/f$, or, $\sim 1/f^2$, etc).[26] Dephasing noise can also take a form that leads to an error in the angle of rotation intended for the qubit state vector (see caption of Figure 2). Error rates for such processes can be quantified using quantum process tomography[27,28] using recently developed protocols such as randomised benchmarking.[29–32]

In addition to dephasing, quantum systems can also suffer from decoherence that involves the emission of a quanta of energy from the system, a photon[33] or phonon[34] for instance, relaxing it from its excited to ground state in a characteristic time, T_1. Over the last decade or so, qubits made from various physical platforms have steadily improved in both dephasing and relaxation times. With some strong exceptions,[35] a good engineering rule-of-thumb is to estimate a typical coherence time today of several tens-of-microseconds for qubits in the solid-state.[9,36,37]

Beyond the single-qubit operations thus described, subsequent control pulses may be applied to cause two qubits to interact such that their evolution becomes conditioned on the properties of the two-qubit state. This later operation leads to quantum entanglement, a phenomena that is at the heart of quantum computation and quantum error correction.[14] From the point-of-view of the control hardware, these two-qubit entangling operations are again produced by generating electromagnetic pulses that act simultaneously on both qubits, with the pair usually labelled as a 'target' and a 'control'.[38,39] In direct correspondence to the universal logic gates underpinning classical information processing (such as, NAND or NOR gates), universal quantum computing can be performed using only single-qubit rotations together with two-qubit entangling operations.

QUANTUM READOUT

The hardware interface must also provide a means of measuring the state of a quantum system, either to uncover the result of a computation, or to track and correct errors as part of a protocol to achieve fault tolerance. Unlike the straightforward acquisition of a classical signal, quantum mechanics does not allow all the information about the system to be extracted in a single measurement.[14,40] Rather, to uncover the complex coefficients c_i of a superposition $\psi = (c_1|g\rangle + c_2|e\rangle)$, the wavefunction ψ must be prepared and measured many times to determine the probability of measurement outcomes 'g' or 'e'.

For solid-state qubits, readout involves either coupling a mesoscale detector device to the quantum system, for instance, a charge sensor[35,41–44] (see Figure 3) or detecting the response of a coupled superconducting cavity resonator[8,9] (see Figure 4). In either case, the dissipative (magnitude) or dispersive (phase) response of the resonator yields a signal that is usually amplified and conditioned before being acquired by sampling a microwave or radio-frequency waveform using an analogue-to-digital converter circuit. Reading out the state of the qubit then amounts to integrating this measurement signal for a period of time to give a single value that is above or below a set threshold, yielding a 'g' or 'e' (see Figure 2).

In further contrast to classical measurements, quantum mechanics also sets limits on the amount of unavoidable noise that must be added to a readout signal by a detector or an amplifier.[45] Today, unavoidable 'quantum noise' makes up a significant fraction of the total noise-budget and sets a bound on how fast a qubit can be measured.[13] The readout detector can also generate a form of back-action that effectively kicks the qubit out of its energy state altogether,[23,40,46] either by coupling too strongly to the quantum system, or because additional, high-frequency noise enters during the readout.[23] Finally, it is worth noting that in several spin systems,[1,35] the readout process is essentially a classical measurement that follows the sudden, forced decoherence of the qubit by its environment.

THE QUANTUM PHYSICAL LAYER

At present it is not possible to determine the ideal physical platform in which to construct ubiquitous quantum technologies. Today a range of platforms have demonstrated few-qubit operations, from trapped ions, single optical photons, spins and superconducting implementations. Each of these has their own advantages and disadvantages. Some of the key parameters in which to benchmark platforms with respect to scale-up include clock speed, coherence time, the fidelity and speed of single- and two-qubit logic gates, readout time, susceptibility to crosstalk, footprint, architectural complexity and the requirements or constraints imposed on the control and readout hardware.

These parameters are not independent and there are trade-offs that intersect many aspects of the classical interface technology. As an example, consider the clock speed of a quantum computer, a clearly important parameter in setting the number of quantum logic gates that can be executed in a coherence time. The clock speed, however, cannot be made arbitrarily fast without adding a considerable burden to the classical hardware needed to control and readout qubits. As the time scale for single-qubit operations in a variety of solid-state systems is today measured in nanoseconds, this already implies that the classical control hardware will likely need to operate at frequencies above a few gHz. Today's commercial off-the-shelf technology can accommodate waveform generation at such data rates, but with a limited number of channels, large footprint and significant power dissipation. Considering that the classical interface hardware of a full-blown quantum machine will additionally need to sample and condition readout signals, as well as perform some level of classical data processing, it becomes clear that new devices, techniques and computing architectures, beyond today's technologies, must be anticipated to operate the classical layer at speeds commensurate with controlling scaled-up quantum logic.

Semiconductor qubits

Semiconductor qubits comprise mostly gate-defined quantum dot systems in which single electron spins[1,47,48] or charges[5] can be controlled, detected and coupled via capacitive interactions or Heisenberg exchange. Additional types of semiconductor qubits include optically active self-assembled quantum dots,[49] systems based on atomic donors, such as phosphorous nuclear spins in silicon[35,50] or colour centres in diamond[51] or related material systems.[4] The semiconductor physical layer may be configured differently to yield distinct 'flavours' of spin qubit, each with significantly different requirements for the interface hardware.

The most straightforward flavour of spin qubit is the single electron spin, proposed by Loss and DiVincenzo.[52] Single Loss and DiVincenzo qubits are controlled using resonant ac magnetic fields[53] (see Figure 2), or ac electric fields by making use of the spin-orbit interaction,[54] a static magnetic field gradient from

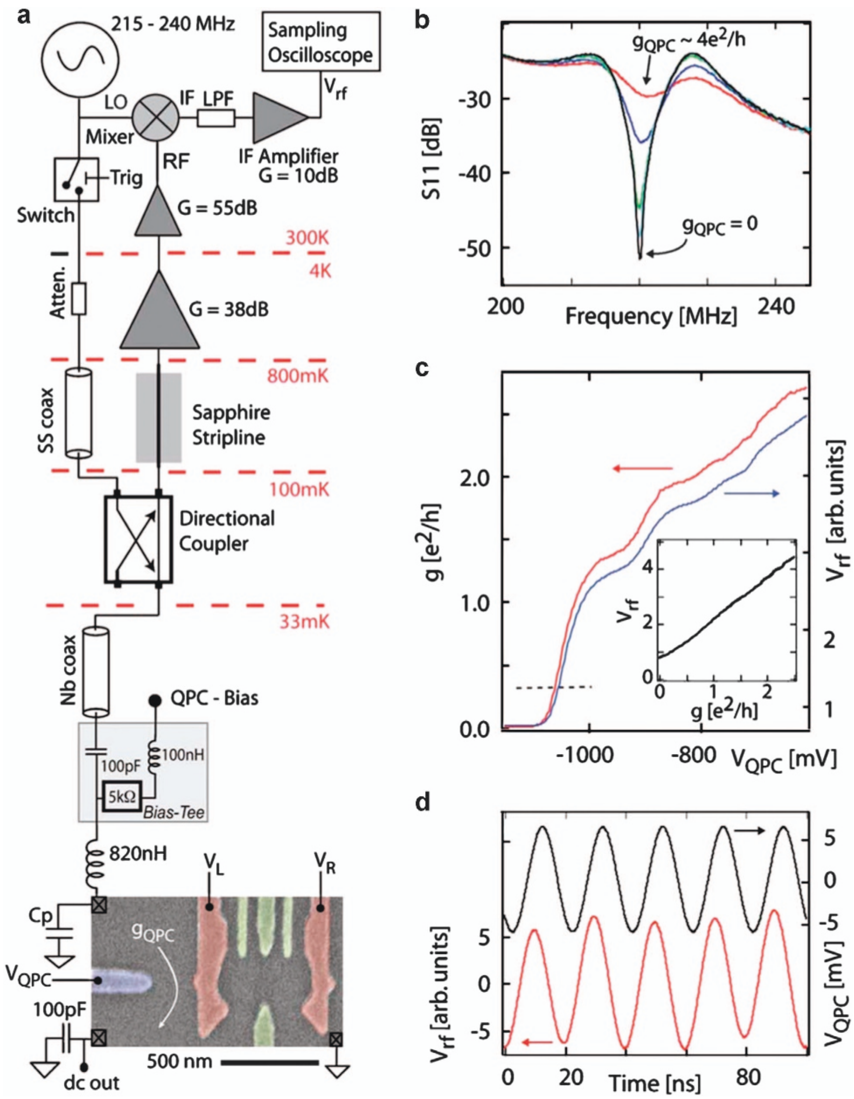

Figure 3. Readout of spin qubits, taken from ref. 44. Singlet-tripet and exchange-only qubits make use of a spin-to-charge conversion process that first maps the relative spin-state of a two-electron system to the charge configuration of a quantum dot. This charge signal is then sensed with an single electron transistor or quantum point contacts (QPCs) electrometer, proximal to the quantum dot system. **a** shows a schematic of measurement set-up for a rf-QPC. **b** shows rf power as a function of QPC resistance. Demodulation is performed by mixing the rf signal with a LO to yield an IF that is low-pass filtered before further amplification and digitisation. **c** and **d** show demodulated response as a function of voltage applied to a gate (see ref. 46 for details).

nuclei[55] or permanent micromagnets on chip.[56] Such gradients also provide a means of selectively addressing individual spins for rotation at a particular frequency, effectively performing MR imaging at the single-qubit level. Readout occurs via charge sensors such as single electron transistors or quantum point contacts, detecting the spin-dependent tunnelling of electrons to adjacent reservoirs or ancilla quantum dots.[1,57] From the perspective of the hardware interface, controlling a single Loss and DiVincenzo qubit requires the generation of microwave pulses with frequency set by the external magnetic field and electron *g*-factor, as well as the production of 'dc' (square wave) pulses to adjust the potential of the quantum dot and its tunnel barriers. These time-dependent waveforms are in addition to the handful of dc voltage biases that are needed to establish the electrostatic potential of the quantum dot system itself.

Singlet–triplet qubits are a flavour of semiconductor qubit constructed from the relative orientation of two-electron spins in a double quantum dot.[58,59] With the cost of needing two electrons per qubit comes the advantage that singlet–triplet qubits do not require ac magnetic or electric fields for single- or two-qubit gates. Rather, the singlet–triplet system makes use of the exchange interaction in conjunction with a static magnetic field gradient produced by nuclear spins,[36,60] or micromagnets.[56] These magnetic field gradients can be done away with entirely by adding a further electron to create a three-electron manifold known as the exchange-only qubit.[61] The advantage of the exchange-only qubit, and its ac variant the resonant exchange qubit,[62] is that it can be controlled solely by electrical means. This is significant in that the exchange energy in these quantum dots systems can be made large enough to operate single- and two-qubit gates on timescales much faster than 1 ns. This time should be considered in the context of coherence times (T_2) that range from 10 s of microseconds to milliseconds for spins in solids.

Superconducting qubits

Similar to the various flavours of spin qubit, superconducting devices can be configured into a variety of platforms for quantum

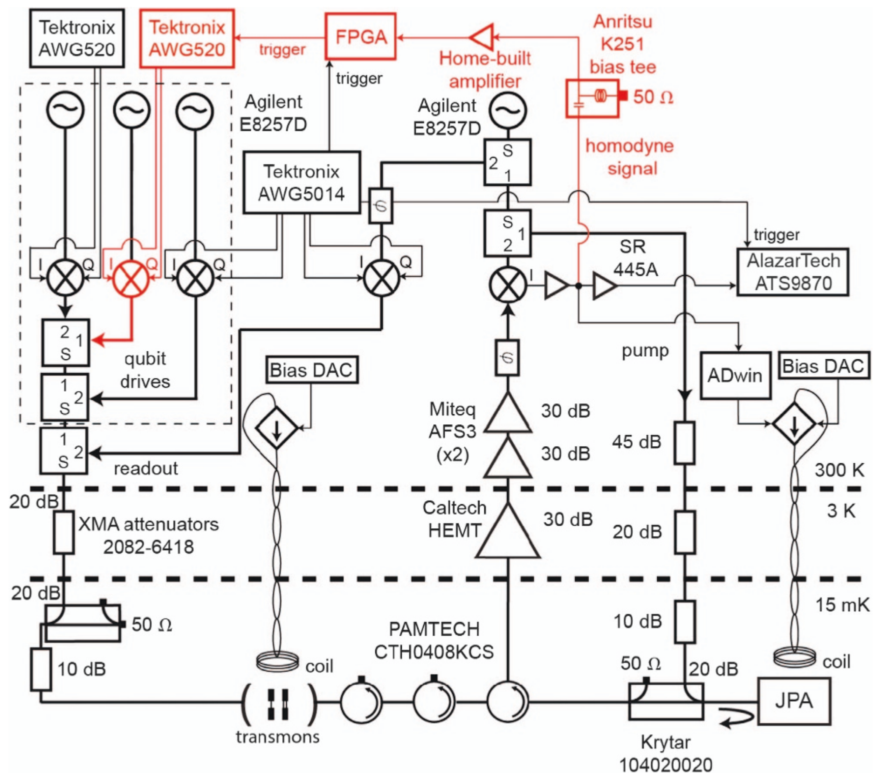

Figure 4. Taken from extended data section of ref. 92. Complete wiring of electronic components outside and inside the 3He/4He dilution refrigerator (Leiden Cryogenics CF-650). Readout and qubit-drive pulses, shaped by a Tektronix AWG5014 and two Tektronix AWG520, enter the cavity via a single transmission line. The cavity output is reflected by the JPA, which is biased by a superconducting coil and a strong pump tone, bending its resonance down to f_P and providing parametric amplification. The signal is further amplified at the 3-K stage (Caltech Cryo1-12) and at room temperature (two Miteq AFS3-04000800-10-ULN amplifiers). Demodulation to baseband is provided by a generator at f_P, also used for readout and pump. Two phase shifters allow adjusting the relative phase between the three tones at f_P. The demodulated signal is split into three separate arms after amplification by a Stanford Research Systems SR445A. One arm stabilises the Josephson Parametric Amplifier (JPA) flux bias via an ADwin-GOLD processor programmed as a PID controller. In the second arm, the signal is filtered by a bias tee, amplified with a custom-built amplifier, and integrated and thresholded by the FPGA. The FPGA conditionally triggers a $Q_A - \pi$ pulse from an AWG520. The third arm connects to an AlazarTech ATS9870 digitizer for data storage and processing after a second SR445A amplification stage. Red colour highlights the key components of the feedback loop. AWG, arbitrary waveform generator.

computing.[63–66] Following an evolution over the last decade that has seen the development of a family of related devices exploiting charge, flux and the super-current phase, the superconducting community has largely converged on an implementation known as the 'transmon'.[67] The key component underpinning all superconducting qubits is the Josephson junction (JJ)—the only known non-linear circuit element that does not dissipate energy. These JJs are constructed as tunnel junctions in which two superconductors, usually aluminium, are separated by a small insulating region, typically an oxide layer. The non-linear aspect of the JJ leads to an energy spectrum with distinct ground and excited states, rather than the ladder of equally spaced states produced by a pure LC oscillator.[63–66] Adjusting the relative strengths of the capacitive, inductive or tunnelling energy, allows the shape of the qubit 'band-structure' to be engineered. Transmon qubits exploit this tunability to create essentially flat bands that are insensitive to charge noise that would otherwise lead to decoherence. For superconducting architectures based on transmons, single-qubit control, two-qubit interactions and qubit readout are all performed by coupling qubits to electric field modes of a microwave cavity or 'bus' using the techniques of circuit quantum electrodynamics.[8,68] These operations are again performed via microwave pulses (see Figure 2) following a calibration procedure to adjust the qubit energies by setting a static flux bias.[8,68]

Topological qubits

It is possible to conceive a very different approach to engineering quantum technology based on solid-state systems that exhibit non-trivial topological degrees-of-freedom, so called 'non-Abelian' quantum phases of matter.[69] These phases allow for quantum information to be encoded nonlocally, protecting it from the usual forms of noise and environmental interactions that lead to decoherence. At present this platform is at an early stage of development but will likely be controlled via means not too different from other solid-state qubit platforms.[7,70] In addition to the potential noise immunity at the layer of physical qubits, fully realised, topological protection may also relax many of the technical constrains affecting the control and readout interface.

Controlling topological qubits involves manipulating the position of composite particles of the system that form a degenerate ground state. Manipulating these quasiparticles should be done slowly, so as to not excite the system. Typically, operations involve exchanging the position of quasiparticles by taking them around each other in a two-dimensional plane or using a network of fused nanowires. Such 'braiding' operations take the system through an evolution that constitutes single- and two-qubit quantum logic gates—processing quantum information by tying knots in the quasiparticle 'world-lines'.[71] At the layer of the hardware interface, braiding operations are performed by controlling the chemical potential of a semiconductor or height of a tunnel barrier or the magnetic flux threading a superconducting loop.[7] Similar to the other qubit systems discussed, logic gates are likely to be performed via the generation and application of particular waveforms that take the quantum system through a time-dependent evolution of its parameters. Reading out the state of topological qubits will likely proceed via charge or flux parity measurements of two separated sections of the quantum circuit using charge-sensing techniques[70] or by probing the dispersive shift of a coupled resonator.[7]

ARCHITECTURES AND HARDWARE INTERFACES

Integrated quantum machinery will comprise a physical layer with embedded qubits, directly coupled to a readout and control interface constructed from classical technologies. Across the three different qubit platforms considered here, common tasks for this interface layer include the generation of semi-static bias voltages and currents, generation of microwave control pulses, and the acquisition of readout signals. In addition, the interface hardware should provide some configurable signal conditioning, classical data processing and means of implementing feedback between readout and control subsystems needed for many routine tasks such as qubit preparation and stabilisation.[72] Feedback will also be likely needed for aspects of error correction and protocols such as entanglement purification.[73]

Over the last few years, the hardware requirements for controlling and reading out qubits have largely converged across the solid-state platforms. The great majority of control operations effectively amount to generating waveforms, typically done via direct digital synthesis (DDS) with an arbitrary waveform generator. The frequency components of these waveforms are in the range of 4–8 GHz for superconducting devices, and typically a little lower for semiconductor qubits, in the range 0.5–2 GHz. For both systems, the width and height of the pulse modulation envelop are comparable, again generated with arbitrary waveform generators with GHz clock rates (see Figure 2).

Note that all of these solid-state systems also have similar requirements in terms of the cryogenic technology used to cool qubit chips and associated hardware. The need for cryogenic environments has also extended recently to qubit platforms based on quantum photonics[74] and trapped ions.[75] As all of these quantum devices advance in complexity and physical footprint, cryogenic systems of the kind that are now in use for high-energy physics experiments will likely be needed to enable complex quantum machines.[76] With scale-up in qubit numbers and density, a particular challenge for cryogenic technology is the heat generated by the control and readout subsystem, either from the use of active circuits at cryogenic temperatures or from large channel-count interconnect technologies that bring heat from higher temperature stages. Ensuring that control signals produce minimal dissipation at the lowest temperature stage of the refrigerator will be essential.

Microarchitectures

Minimising the overhead on classical hardware resources will be crucial in addressing the challenge of scaling-up quantum technology. Beyond the ‘brute-force’ approach of directly wiring every qubit to its own dedicated readout and control hardware, scale-up techniques can make use of multiplexing and switching circuits[77–81] that share resources across the interface, or schemes that allow universal computation with highly compressed gate-sets. These methods are yet to be fully evaluated in terms of their impact on error correcting codes.[21] To what extent error correction can function in the face of practical constraints, for instance, using realistic readout times or inhomogeneous qubit–qubit coupling strengths, is an open area of research.

Further simplification of the control interface is possible if qubits remain stable over long periods of time. Without this luxury, qubit parameter calibration protocols will likely take up much of the classical hardware resources. For certain types of qubits and noise sources, this challenge may be in part addressed by optimal control approaches that dynamically decouple low frequency fluctuations and system drifts from qubit evolution using composite pulse sequences.[17,24–26]

Control technology

Quantum computation is today largely the domain of basic research that relies on commercially available equipment to construct experiments in the laboratory. On the control side, common components include microwave and arbitrary waveform generators to produce control pulses and digital-to-analogue converters to produce bias signals. These are typically combined with passive components such as mixers, filters, bias-tees and splitter-combiner networks (see Figure 4). The next generation of experiments that involve tens of qubits, however, will begin to encounter a level of complexity in the control interface as to warrant a new approach for integrating these components to improve their performance. Avenues for improvement include dramatically increasing the number, density and modularity of independent control channels, signal bandwidth, the time and amplitude resolution of generated waveforms, and the physical footprint of circuits and interconnects (see Figure 5).

For many platforms, the noise performance of the control system is paramount in determining the fidelity of operations and coherence of qubits. Relevant noise specifications include both amplitude and phase noise, as well as common-mode noise that leads to correlated errors between qubits that are nominally uncoupled. Such correlated noise sources have implications for the performance of error correcting codes.[82] From an engineering perspective, a further consideration is the noise performance of the control system out-of-band, at frequencies far from the intended operating bandwidth of the instrument, but of detriment to the performance of qubits. Given that quantum systems can be configured as the most sensitive and wide-band spectrometers of noise available[23,83] combating all sources of noise from control instrumentation will remain an on-going challenge. Technologies for improving the performance of control hardware include chip-sets based on next-generation silicon-complementary metal–oxide–semiconductor (CMOS) processes, as well as alternate material systems, for example, BiCMOS platforms, SiGe,[84] and III–V compounds such as GaAs and InP.[85] Devices based on these alternate materials are of particular interest in the low-noise, microwave domain required for qubit control.

A further consideration is the possibility of also embedding aspects of the control system at cryogenic temperatures so that it may be directly integrated with the quantum physical layer. This level of integration, while not necessary today, has potential to significantly improve the performance of interface hardware in controlling large numbers of qubits. Cryogenic operation would enable signal paths between the quantum and classical interface to be minimised, avoiding latency, timing and synchronisation issues associated with the propagation and dispersion of analogue and digital signals at high clock frequencies over large distances. Locating control and readout circuits proximal to the qubits would lead to a dramatic reduction in their operating temperature, an aspect that if taken into account in the design of circuits can also result in devices with improved noise performance. The advent of cryogenic control hardware would also enable many practical improvements such as the use of miniaturised, superconducting interconnects for increasing the density of wiring inside a dilution refrigerator.[86,87] Similar approaches have long been used in the astronomy and space communities.[88]

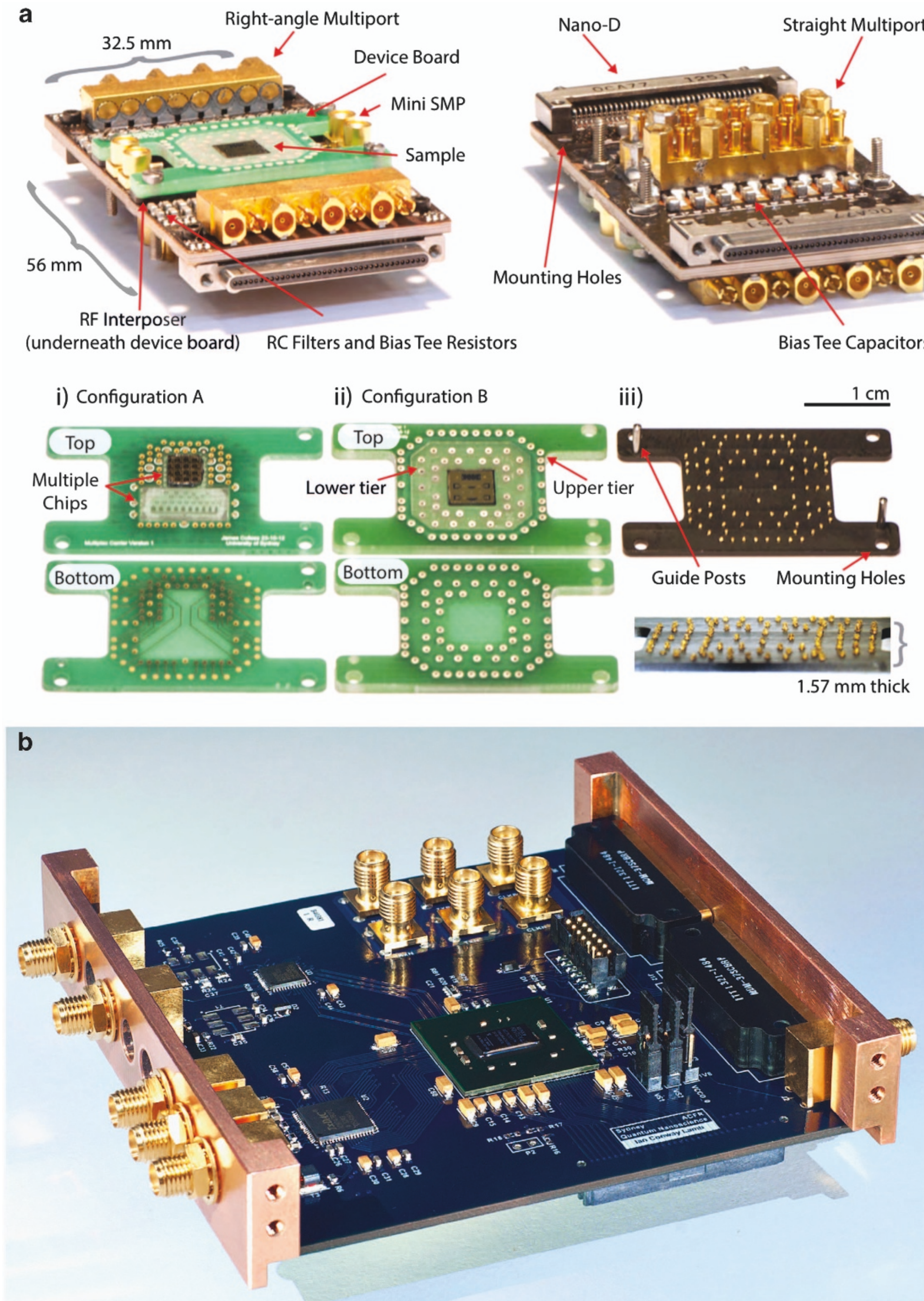

Figure 5. Example elements of the classical-quantum interface. **a** (taken from ref. 99) shows modular cryogenic circuit board interconnects designed to interface a large number of readout and control channels with scaled-up spin qubit devices. **b** shows a photograph of a cryogenic platform for implementing fast feedback between readout and control. The system integrates a high-speed digital-to-analogue converter and ADC with a commercially available FPGA, made to operate at cryogenic temperatures (see ref. 100 for details).

The need for control hardware that is low noise, high speed, but sufficiently low in power consumption to enable deep cryogenic operation may ultimately lead to the use of platforms deploying classical superconducting logic. Circuits based on rapid single flux quantum technology,[89] or, its modern ultra-low power cousin, reciprocal quantum logic,[90] are now reaching complexity levels that makes them viable alternatives to high-speed, low-power CMOS. As these superconducting technologies continue to improve, particularly in terms of the infrastructure needed to design and test complex circuits, they may well become the ideal platform in which to construct the control hardware interface for large-scale quantum machines. Towards this goal, the realisation of high-speed cryogenic memory circuits will be vital.

In addition to data converters such as digital-to-analogue converters and analogue-to-digital converters that transfer data between the quantum layer and control interface, a means of performing high-speed classical computation will also be needed to implement many of the protocols associated with executing a fault-tolerant algorithm. For room temperature control systems, these will likely comprise highly parallel data processing solutions based on FPGAs with soft-core processors or even CPUs/GPUs. At cryogenic temperatures, however, power constraints will drive a need for application-specific integrated circuits designed from the ground-up to operate quantum computing devices (see Figure 1).

Readout technology

For both semiconducting and superconducting devices considered in this review, the time scale in which to perform qubit readout in a single-shot is converging to around a few 100 ns (for ~99% fidelity). This is the time over which the readout signal must be integrated to determine the state of qubit, and for a perfectly efficient readout system also corresponds to the time over which the qubit evolves into the state determined by the measurement (see Figure 2). Although some small further improvement is possible, the readout time is set by quantum mechanical limits on the minimum noise added by amplifiers and detection systems, and also by the achievable strength of electromagnetic coupling between a qubit and readout device. In comparison to the typical time to execute single- and two-qubit gates in the solid-state, the readout time poses a bottleneck to many of the standard operations needed for quantum computation.

From an engineering perspective, reading out the state of condensed matter qubits amounts to exciting a resonator, and then acquiring both the magnitude and phase of the response signal. For today's spin qubits that make use of lumped-element LC resonators coupled to charge or capacitance sensors,[43,44,91] operating frequencies in the 0.1–1 GHz band are typical. The superconducting community has largely made use of distributed transmission line resonators for readout and control, operating in the 4–8 GHz range.[9,92] Both configurations rely heavily on the use of low noise cryogenic amplifiers (usually based on high-electron mobility transistors) to boost the signal before it emerges from the dilution refrigerator. Recently these high-electron mobility transistors have been proceeded with amplification devices operating close to quantum limits in terms of noise performance. Examples include the Josephson parametric amplifiers that exploit the non-linearity associated with the inductance of a JJ to achieve four-wave mixing and amplification.[93–95] Such set-ups suffer from an inconvenience in that they require the use of bulky circulators—microwave components that use permanent magnets to yield non-reciprocal circuit parameters. Dramatically shrinking these circulators or doing away with them altogether will be advantageous for scaling-up readout systems.[96,97]

The number of separate parallel amplification chains needed can be greatly reduced by using frequency domain multiplexing techniques that assign a separate frequency to each resonator or qubit.[9,78,92] Given the bandwidth of each resonator, however, and allowing for sufficient separation in frequency channels to avoid crosstalk, the number of channels is limited to 10–100 per wide-band amplification chain. Improvements in performance of low-noise microwave amplifiers can increase this number, but alternate methods, such as time-domain interleaving, are likely needed to acquire readout signals from large numbers of qubits and resonators. A further approach is to integrate separate small amplifiers and few-bit analogue-to-digital converters on chip for each readout channel, generating highly multiplexed digital readout data before emerging from the cryostat. Such an approach may become viable in future using superconducting logic circuits.[98]

Finally, it is worth considering the requirements for the readout interface from the perspective of qubit calibration and verification. Beyond the output of a quantum algorithm, in a debugging and trouble-shooting mode the readout subsystem must allow for measurements that are outside the binary outcome for the state of a qubit. This is especially true when tuning-up qubit systems, either by adjusting the voltage-bias on surface gates that define quantum dots, or in configuring the flux biases that set the qubit transition frequencies in superconducting devices. Techniques from computer science such as machine learning, as well as sophisticated approaches developed to process 'big data' sets will likely find relevance in controlling and calibrating quantum systems of the future.

FUTURE OUTLOOK

In the last decade or so, quantum computing in the solid-state has progressed from mostly a theoretical idea to the experimental realisation of few-qubit devices in the laboratory. The field has now advanced to the level where, in parallel with continued basic research, a focused engineering effort is needed to address the challenges of integrating and controlling complex quantum machines. Not only is this effort needed to realise quantum technology in the long term, but is also a key in establishing the next generation of tools and experiments that probe many fundamental aspects of these artificial quantum systems.

In the next decade, technology development in support of quantum science will establish new platforms and approaches to engineering materials, software systems, cryogenic equipment and electronics. Integrating these platforms, beyond just bringing together off-the-shelf products, will pose new challenges and require interdisciplinary approaches to devising solutions. 'Quantum engineers' will continue to speak the language of quantum mechanics while devising complex microwave circuits that function at mK temperatures, programme FPGA systems that implement quantum error correction protocols or model crosstalk in circuit boards to extend qubit coherence. The nascent field of quantum engineering will also play a pivotal role in uncovering and articulating the challenges for scaling-up quantum devices into computationally useful machines.

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COMPETING INTERESTS

The authors declare no conflict of interest.

REFERENCES

1 Hanson R, Kouwenhoven LP, Petta JR, Tarucha S, Vandersypen LMK. Spins in few-electron quantum dots. *Rev Mod Phys* 2007; **79**: 1217–1265.
2 Kane BE. A silicon-based nuclear spin quantum computer. *Nature (London)* 1998; **393**: 133.
3 Pla JJ, Mohiyaddin FA, Tan KY, Dehollain JP, Rahman R, Klimeck G *et al.* Coherent control of a single ^{29}Si nuclear spin qubit. *Phys Rev Lett* 2014; **113**: 246801.
4 Christle DJ, Falk AL, Andrich P, Klimov PV, Hassan JU, Son NT *et al.* Isolated electron spins in silicon carbide with millisecond coherence times. *Nat Mater* 2015; **14**: 160–163.
5 Petta JR, Johnson AC, Marcus CM, Hanson MP, Gossard AC. Manipulation of a single charge in a double quantum dot. *Phys Rev Lett* 2004; **93**: 186802.
6 Mourik V, Zuo K, Frolov SM, Plissard SR, Bakkers EPAM, Kouwenhoven LP. Signatures of majorana fermions in hybrid superconductor-semiconductor nanowire devices. *Science* 2012; **336**: 1003–1007.
7 Hyart T, van Heck B, Fulga IC, Burrello M, Akhmerov AR, Beenakker CWJ. Flux-controlled quantum computation with majorana fermions. *Phys Rev B* 2013; **88**: 035121.
8 Wallraff A, Schuster DI, Blais A, Frunzio L, Huang R-S, Majer J *et al.* Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics. *Nature* 2004; **431**: 162–167.
9 Kelly J, Barends R, Fowler AG, Megrant A, Jeffrey E, White TC *et al.* State preservation by repetitive error detection in a superconducting quantum circuit. *Nature* 2015; **519**: 66–69.

10 Ladd TD, Jelezko F, Laflamme R, Nakamura Y, Monroe C, O'Brien JL. Quantum computers. *Nature* 2010; **464**: 45–53.
11 Houck AA, Tureci HE, Koch J. On-chip quantum simulation with superconducting circuits. *Nat Phys* 2012; **8**: 292–299.
12 Acosta V, Hemmer P. Nitrogen-vacancy centers: physics and applications. *MRS Bull* 2013; **38**: 127–130.
13 Devoret MH, Schoelkopf RJ. Amplifying quantum signals with the single-electron transistor. *Nature* 2000; **406**: 1039–1046.
14 Nielsen MA, Chuang IL. *Quantum Computation and Quantum Information: Cambridge Series on Information and the Natural Sciences*. Cambridge University Press: Cambridge, UK, 2000.
15 Zurek WH. Decoherence, einselection, and the quantum origins of the classical. *Rev Mod Phys* 2003; **75**: 715–775.
16 Bertsekas DP. *Dynamic Programming and Optimal Control*. 2nd edn Athena Scientific: 2000.
17 Viola L, Knill E. Robust dynamical decoupling of quantum systems with bounded controls. *Phys Rev Lett* 2003; **90**: 037901.
18 Bravyi S, Kitaev A. Quantum codes on a lattice with boundary. Preprint at arXiv:quant-ph/9811052, 1998.
19 Raussendorf R, Harrington J. Fault-tolerant quantum computation with high threshold in two dimensions. *Phys Rev Lett* 2007; **98**: 190504.
20 Gottesman D. Introduction to quantum error correction and fault-tolerant quantum computation. Preprint at arXiv:0904.2557v1, 2009.
21 Dennis E, Kitaev A, Landahl A, Preskill J. Topological quantum memory. *J Math* 2002; **43**: 4452.
22 Fukushima E, Roeder SBW. *Experimental Pulse NMR: A Nuts and Bolts Approach, Advanced book program*. Addison-Wesley, 1993.
23 Martinis JM, Nam S, Aumentado J, Lang KM, Urbina C. Decoherence of a superconducting qubit due to bias noise. *Phys Rev B* 2003; **67**: 094510.
24 Khodjasteh K, Lidar D. Performance of deterministic dynamical decoupling schemes: Concatenated and periodic pulse sequences. *Phys Rev A* 2007; **75**: 062310.
25 Biercuk MJ, Uys H, VanDevender AP, Shiga N, Itano1 WM, Bollinger JJ. Optimized dynamical decoupling in a model quantum memory. *Nature* 2009; **458**: 996–1000.
26 Barthel C, Medford J, Marcus CM, Hanson MP, Gossard AC. Interlaced dynamical decoupling and coherent operation of a singlet-triplet qubit. *Phys Rev Lett* 2010; **105**: 266808.
27 Emerson J, Alicki R, Zyczkowski K. Scalable noise estimation with random unitary operators. *J Opt B* 2005; **7**: S347.
28 Chuang Isaac L, Nielsen MA. Prescription for experimental determination of the dynamics of a quantum black box. *J Mod Opt* 1997; **44**: 2455–2467.
29 Poyatos JF, Cirac JI, Zoller P. Complete characterization of a quantum process: The two-bit quantum gate. *Phys Rev Lett* 1997; **78**: 390–393.
30 Magesan E, Gambetta JM, Johnson BR, Ryan CA, Chow JM, Merkel ST *et al.* Efficient measurement of quantum gate error by interleaved randomized benchmarking. *Phys Rev Lett* 2012; **109**: 080505.
31 Gaebler JP, Meier AM, Tan TR, Bowler R, Lin Y, Hanneke D *et al.* Randomized benchmarking of multiqubit gates. *Phys Rev Lett* 2012; **108**: 260503.
32 Wallman JJ, Flammia ST. Randomized benchmarking with confidence. *N J Phys* 2014; **16**: 103032.
33 Houck AA, Schreier JA, Johnson BR, Chow JM, Koch J *et al.* Controlling the spontaneous emission of a superconducting transmon qubit. *Phys Rev Lett* 2008; **101**: 080502.
34 Fujisawa T, Oosterkamp TH, van der Wiel WG, Broer BW, Aguado R, Tarucha S *et al.* Spontaneous emission spectrum in double quantum dot devices. *Science* 1998; **282**: 932–935.
35 Pla JJ, Tan KY, Dehollain JP, Lim WH, Morton JJL, Jamieson DN *et al.* A single-atom electron spin qubit in silicon. *Nature (London)* 2012; **489**: 541.
36 Bluhm H, Foletti S, Neder I, Rudner M, Mahalu D, Umansky V *et al.* Dephasing time of gaas electron-spin qubits coupled to a nuclear bath exceeding 200 us. *Nat Phys* 2010; **7**: 109–113.
37 Paik H, Schuster DI, Bishop LS, Kirchmair G, Catelani G, Sears AP *et al.* Observation of high coherence in josephson junction qubits measured in a three-dimensional circuit qed architecture. *Phys Rev Lett* 2011; **107**: 240501.
38 DiCarlo L, Reed MD, Sun L, Johnson BR, Chow JM, Gambetta JM *et al.* Preparation and measurement of three-qubit entanglement in a superconducting circuit. *Nature* 2010; **467**, 574–578.
39 Shulman MD, Dial OE, Harvey SP, Bluhm H, Umansky V, Yacoby A. Demonstration of entanglement of electrostatically coupled single-triplet qubits. *Science* 2012; **336**: 202–205.
40 Braginsky VB, Braginskil VB, Khalili FY, Thorne KS. *Quantum Measurement*. Cambridge University Press: Cambridge, UK, 1995.
41 Field M, Smith CG, Pepper M, Ritchie DA, Frost JEF, Jones GAC *et al.* Measurements of coulomb blockade with a noninvasive voltage probe. *Phys Rev Lett* 1993; **70**: 1311–1314.
42 Lu W, Ji Z, Pfeiffer LN, West KW, Rimberg AJ. Real-time detection of electron tunneling in a quantum dot. *Nature (London)* 2003; **423**: 422.
43 Barthel C, Reilly DJ, Marcus CM, Hanson MP, Gossard AC. Rapid single-shot measurement of a singlet-triplet qubit. *Phys Rev Lett* 2009; **103**: 160503.
44 Reilly DJ, Marcus CM, Hanson MP, Gossard AC. Fast single-charge sensing with a rf quantum point contact. *App Phys Lett* 2007; **91**: 162101.
45 Caves CM. Quantum limits on noise in linear amplifiers. *Phys Rev D* 1982; **26**: 1817–1839.
46 Granger G, Taubert D, Young CE, Gaudreau L, Kam A, Studenikin SA *et al.* Quantum interference and phonon-mediated back-action in lateral quantum-dot circuits. *Nat Phys* 2012; **8**: 522–527.
47 Maune BM, Borselli MG, Huang B, Ladd TD, Deelman PW, Holabird KS *et al.* Coherent singlet-triplet oscillations in a silicon-based double quantum dot. *Nature* 2012; **481**: 344–347.
48 Veldhorst M, Hwang JCC, Yang CH, Leenstra AW, de Ronde B, Dehollain JP *et al.* An addressable quantum dot qubit with fault-tolerant control-fidelity. *Nat Nanotechnol* 2014; **9**: 981–985.
49 Gywat O, Krenner HJ, Berezovsky J. *Spins in Optically Active Quantum Dots: Concepts and Methods*. John Wiley & Sons, 2010.
50 Muhonen JT, Dehollain JP, Laucht A, Hudson FE, Kalra R, Sekiguchi T *et al.* Storing quantum information for 30 seconds in a nanoelectronic device. *Nat Nanotechnol* 2014; **9**: 986–991.
51 Childress L, Hanson R. Diamond nv centers for quantum computing and quantum networks. *MRS Bull* 2013; **38**: 134–138.
52 Loss D, DiVincenzo D. Quantum computation with quantum dots. *Phys Rev A* 1998; **57**: 120.
53 Koppens FHL, Buizert C, Tielrooij KJ, Vink IT, Nowack KC, Meunier T *et al.* Driven coherent oscillations of a single electron spin in a quantum dot. *Nature* 2006; **442**: 3443.
54 Nowack KC, Koppens FHL, Nazarov YuV, Vandersypen LMK. Coherent control of a single electron spin with electric fields. *Science* 2007; **318**: 1430–1433.
55 Laird EA, Barthel C, Rashba EI, Marcus CM, Hanson MP, Gos-sard AC. Hyperfine-mediated gate-driven electron spin resonance. *Phys Rev Lett* 2007; **99**: 246601.
56 Yoneda J, Otsuka T, Nakajima T, Takakura T, Obata T, Pioro-Ladriere M *et al.* Fast electrical control of single electron spins in quantum dots with vanishing influence from nuclear spins. *Phys Rev Lett* 2014; **113**: 267601.
57 Nowack KC, Shafiei M, Laforest M, Prawiroatmodjo GEDK, Schreiber LR, Reichl C *et al.* Single-shot correlations and two-qubit gate of solid-state spins. *Science* 2011; **333**: 1269.
58 Levy J. Universal quantum computation with spin-1/2 pairs and heisenberg exchange. *Phys Rev Lett* 2002; **89**: 147902.
59 Petta JR, Johnson AC, Taylor JM, Laird EA, Yacoby A, Lukin MD *et al.* Coherent manipulation of coupled electron spins in semiconductor quantum dots. *Science* 2005; **309**: 2180–2184.
60 Foletti S, Bluhm H, Mahalu D, Umansky V, Yacoby A. Universal quantum control of two-electron spin quantum bits using dynamic nuclear polarization. *Nat Phys* 2009; **5**: 903–908.
61 Medford J, Beil J, Taylor JM, Bartlett SD, Doherty AC, Rashba EI *et al.* Self-consistent measurement and state tomography of an exchange-only spin qubit. *Nat Nanotechnol* 2013; **8**: 654–659.
62 Medford J, Beil J, Taylor JM, Rashba EI, Lu H, Gossard AC *et al.* Quantum-dot-based resonant exchange qubit. *Phys Rev Lett* 2013; **111**: 050501.
63 Devoret MH, Schoelkopf RJ. Superconducting circuits for quantum information: an outlook. *Science* 2013; **339**: 1169–1174.
64 Devoret MH, Martinis JM. Implementing qubits with superconducting integrated circuits. *Quant Inf Proc* 2004; **3**: 381.
65 Schoelkopf RJ, Girvin SM. Wiring up quantum systems. *Nature* 2008; **451**: 664.
66 Clarke J, Wilhelm FK. Superconducting quantum bits. *Nature* 2008; **453**: 1031.
67 Koch J, Yu TM, Gambetta J, Houck AA, Schuster DI, Majer J *et al.* Charge-insensitive qubit design derived from the cooper pair box. *Phys Rev A* 2007; **76**: 042319.
68 Majer J, Chow JM, Gambetta JM, Koch J, Johnson BR, Schreier JA *et al.* Coupling superconducting qubits via a cavity bus. *Nature* 2007; **449**: 443–447.
69 Stern A, Lindner NH. Topological quantum computation from basic concepts to first experiments. *Science* 2013; **339**: 1179.
70 Ben-Shach G, Haim A, Appelbaum I, Oreg Y, Yacoby A, Halperin BI. Detecting majorana modes in one-dimensional wires by charge sensing. *Phys Rev B* 2015; **91**: 045403.
71 Stern A, von Oppen F, Mariani E. *Phys Rev B* 2004; **70**: 205338.
72 Shulman MD, Harvey SP, Nichol JM, Bartlett SD, Doherty AC, Umansky V *et al.* Suppressing qubit dephasing using real-time hamiltonian estimation. *Nat Commun* 2014; **5**: 5156.
73 Bravyi S, Kitaev A. Universal quantum computation with ideal clifford gates and noisy ancillas. *Phys Rev A* 2005; **71**: 022316.

74 O'Brien JL, Furusawa A, Vuckovic J. Photonic quantum technologies. *Nat Photonics* 2009; **3**: 687–695.
75 Niedermayr M, Lakhmanskiy K, Kumph M, Partel S, Edlinger J, Brownnutt M *et al.* Cryogenic surface ion trap based on intrinsic silicon. *N J Phys* 2014; **16**: 113068.
76 Schaeffer D, Nucciotti A, Alessandria F, Ardito R, Barucci M, Risegari L *et al.* The cryostat of the cuore project, a 1-ton scale cryogenic experiment for neutrinoless double beta decay research. *J Phys* 2009; **150**: 012042.
77 Hornibrook JM, Colless JI, Conway Lamb ID, Pauka SJ, Lu H, Gossard AC *et al.* Cryogenic control architecture for large-scale quantum computing. *Phys Rev Appl* 2015; **3**: 024010.
78 Hornibrook JM, Colless JI, Mahoney AC, Croot XG, Blanvillain S, Lu H *et al.* Frequency multiplexing for readout of spin qubits. *App Phys Lett* 2014; **104**: 103108.
79 Al-Taie H, Smith LW, Xu B, See P, Griffiths JP, Beere HE *et al.* Cryogenic on-chip multiplexer for the study of quantum transport in 256 split-gate devices. *Appl Phys Lett* 2013; **102**: 243102.
80 Puddy RK, Smith LW, Al-Taie H, Chong CH, Farrer I, Griffiths JP *et al.* Multiplexed charge-locking device for large arrays of quantum devices. *Appl Phys Lett* 2015; **107**: 143501.
81 Ward DR, Savage DE, Lagally MG, Coppersmith SN, Eriksson MA. Integration of on-chip field-effect transistor switches with dopantless Si/SiGe quantum dots for high-throughput testing. *Appl Phys Lett* 2013; **102**: 213107.
82 Aharonov D, Kitaev A, Preskill J. Fault-tolerant quantum computation with long-range correlated noise. *Phys Rev Lett* 2006; **96**: 050504.
83 Dial OE, Shulman MD, Harvey SP, Bluhm H, Umansky V, Yacoby A. Charge noise spectroscopy using coherent exchange oscillations in a singlet-triplet qubit. *Phys Rev Lett* 2013; **110**: 146804.
84 Cressler JD. Silicon-germanium as an enabling technology for extreme environment electronics. *IEEE Trans Dev Mater Reliab* 2010; **10**: 437.
85 Samoska LA. An overview of solid-state integrated circuit amplifiers in the submillimeter-wave and thz regime. *IEEE Trans THz Sci Technol* 2011; **1**: 9.
86 Tighe TS, Akerling G, Smith AD. Cryogenic packaging for multi-GHz electronics. *IEEE Trans Appl Supercond* 1999; **9**: 3173.
87 van Weers HJ, Kunkel G, Lindeman MA, Leeman M. Niobium flex cable for low temperature high density interconnects. *Cryogenics* 2013; **55-56**: 1–4.
88 Mantooth HA, Cressler John D (eds). *Extreme Environment Electronics*. CRC Press, (Taylor & Francis Group): Boca Raton, London, New York, 2013.
89 Likharev KK, Semenov VK. Rsfq logic/memory family: A new josephson-junction technology for sub-terahertz-clock-frequency digital systems. *IEEE Trans Appl Superconductivity* 1991; **1**: 3.
90 Herr QP, Herr AY, Oberg OT, Ioannidis AG. Ultra-low-power superconductor logic. *J Appl Phys* 2011; **109**: 103903.
91 Colless JI, Mahoney AC, Hornibrook JM, Doherty AC, Lu H, Gossard AC *et al.* Dispersive readout of a few-electron double quantum dot with fast rf gate sensors. *Phys Rev Lett* 2013; **110**: 046805.
92 Riste D, Dukalski M, Watson CA, de Lange G, Tiggelman MJ, Blanter YaM *et al.* Deterministic entanglement of superconducting qubits by parity measurement and feedback. *Nature* 2013; **502**: 350–354.
93 Castellans-Beltran MA, Lehnert KW. Widely tunable parametric amplifier based on a superconducting quantum interference device array resonator. *Appl Phys Lett* 2007; **91**: 083509.
94 Bergeal N, Schackert F, Metcalfe M, Vijay R, Manucharyan VE, Frunzio L *et al.* Phase-preserving amplification near the quantum limit with a josephson ring modulator. *Nature* 2010; **465**: 64–68.
95 Hatridge M, Vijay R, Slichter DH, John Clarke, Siddiqi I. Dispersive magnetometry with a quantum limited squid parametric amplifier. *Phys Rev B* 2011; **83**: 134501.
96 Kerckhoff J, Lalumire K, Chapman BJ, Blais A, Lehnert KW. *On-chip superconducting microwave circulator from synthetic rotation. Preprint at arXiv:150206041*, 2015.
97 Viola G, DiVincenzo DP. Publisher's note: Hall effect gyrators and circulators [phys. rev. x 4, 021019 (2014)]. *Phys Rev X* 2014; **4**: 039902.
98 Mukhanov OA. History of superconductor analog to digital converters. In: Rogalla H, Kes P (eds). *100 years of superconductivity*. Taylor and Francis: London, UK, 2011: 440-458.
99 Colless JI, Reilly DJ. Modular cryogenic interconnects for multi-qubit devices. *Rev Sci Instrum* 2014; **85**: 114706.
100 Conway Lamb ID *et al.* An FPGA-based instrumentation platform for use at deep cryogenic temperatures. Preprint at arXiv:1509.06809, 2015.