Coherent Transport in the Solid State: A Literature Review

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1 Introduction

Quantum computing holds many promising applications in science and industry. In this review we discuss the historial context, delve into more recent developments in solid-state systems, and outline the next experimental steps required in the development of solid-state coherent transport.

In 1982 Paul Benioff proposed [1] the first recognisable theoretical framework for a quantum computer. That same year, Feynman discussed the impossibility of simulating quantum systems with classical computers [2]. Feynman also pushed the idea of controlled manipulation of coherent quantum states in a 1986 book [3]. Deutsch [4] showed that a quantum computer could be exponentially faster than a classical computer.

Quantum computing remained a niche interest until 1994, when Shor proposed his factorization algorithm[1]. This sparked widespread interest as it could be applied to break the public-key cryptography algorithm RSA, used almost ubiquitously for communication security by businesses, banks, militaries and the ssh and https protocols. Shor's algorithm for factorizing large numbers was exponentially faster than anything a modern classical computer could achieve. Widespread interest was aroused.

In 1998, Bruce Kane followed up on Seth Lloyd's more feasible theoretical construction [7][2] with a concrete architecture based on the spin-$\frac{1}{2}$ nucleus of phosphorus embedded in a "spinless" solid silicon-28 matrix and controlled with classical electrical gates [8]. Other architectures based on (among others) photons, trapped ions and superconductors followed [9, 10].

Harking back to Feynman's original predictions, Lanyon et. al. have recently used a photonic quantum computer to perform a simple quantum chemistry calculation: calculating the energy levels of atomic hydrogen [11]. This problem is well known and has been performed on modern classical computers, but the scalability of quantum computing promises much more complex simulations and determinations of molecular properties well out of reach of any current or future classical supercomputer. A new understanding of chemistry and biology would likely result, having widespread applications in materials processing, medicine, drug design and biological and chemical engineering.

No past or future classical computer can fully simulate a quantum system with more than about 50 interacting two-level systems. This corresponds to about $2^{50} = 10^{15}$ different interactions that must be stored in memory and recalculated at each time step. A quantum computer, however, could potentially perform such a simulation using just 50 qubits. This is a very good reason to build a quantum computer.

Coherently controlled quantum devices also have important applications as sensors. SQUIDs form the basis for the definitions and accurate measurement of voltage and magnetic field, and diamond and trapped ion quantum devices have been proposed for use in sensing applications [12, 13].

2 Potential Architectures

Since the proposal by Kane, various architectures have been proposed as ways to build a quantum computer. [10] is a comprehensive review. Normally the "Divincenzo Criteria" [14] are used to quantify the progress using various architectures, however we choose the following, more subjective approach as it is more relevant to experiments. Some of the most important tradeoffs involved in choice of architecture are:

1. coherence time (how long you have to perform computations before your qubits decohere). This should also take into consideration the interaction and transport times between qubits.

[1] [5] is the original article; an excellent "man on the street" explanation is [6]

[2] which contains the first published mention of the word "qubit"

Architecture	Coherence	Scalability	Transport	Interact	Manipulation	Manufacture
Kane type	9	9	1	3	4	2
NMR liquid	3	1	1	8?	8	9
Photonic	3	3	9	4	9	8
GaAs QDs	2	8	5	7	9	8
P in Si - e^{-}spin	7	9	3	3	7	3
Ion Traps	9	6	8	6	9	7
Superconductors	5	7	3	5	8	6
Diamond NV	8	7	5	3	7	6

Table 1: Architecture advantages and disadvantages. Each property is subjectively rated on a scale of 1-9 (9 being the best)

2. scalability (a device must scale to several thousand qubits to be really useful)
3. transport ease (how easy it is to transport qubits on demand with currently known methods)
4. interaction ease (how easy it is to coherently interact two qubits)
5. manipulation ease (how easy it is to set/read a single qubit on demand without interfering with the others)
6. manufacturability (how easy it is to make)

Kane A Kane-type quantum computer [8] is a solid-state device consisting of phosphorus atoms in a silicon lattice, and using the nuclear spin of the phosphorus atom as the qubit (Figure 1). Manipulation and readout is performed using metallic wires on the surface of the silicon. It's very hard to interact with this qubit as the nucleus is deeply buried in a sea of electrons. Transport is also difficult as the state must be transferred coherently to an electron spin, that electron must be coherently transported through the silicon lattice, and then the state must be transferred back to a different nucleus. Both of these problems are solved by the ion trap method (below), which removes the supporting silicon lattice completely. One attraction of this architecture are that many of the processing steps (such as gate fabrication and crystalline-silicon growth) are well understood by the conventional semiconductor manufacturing industry. Another attraction is that the system should have reasonably long coherence times, especially if no-net-nuclear-spin Si-28 is used for the supporting lattice.

The problem of charge traps in the oxide stealing the electron from donor atoms may need to be solved by using something other than the conventional silicon dioxide to separate the gates. Kane suggests SiGe.

Recent progress has demonstrated coherent control of P nuclear spins via the unpaired electron [15]. A recent variation [16] on the original proposal simplifies some aspects of this architecture by only requiring localised readout of a 2D array (and having entanglement generated globally).

A theoretical treatment of nuclear spin coherence decay via spin-orbit coupling and phonon emission is given in [17].

NMR Liquid NUCLEAR MAGNETIC RESONANCE was first performed in 1940s. In this approach, molecules with several interacting nuclear spins are affected by global fields. Different "qubits" are addressed by tuning the resonating microwave field frequency or magnetic field strength.

Such qubits were demonstrated by IBM [18, 19], who arguably performed Shor's algorithm to factorize the number 15, with some questions as to whether there was any coherent entanglement. This method is not scalable past a few qubits due to the method of addressing individual qubits.

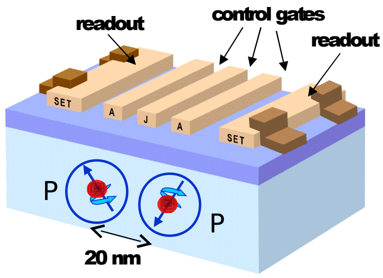


Figure 1: Si:P interaction zone (courtesy David Jamieson).

Recently, solid-state NMR quantum computers have been investigated. Due to the lack of molecular drift (changing magnetic field and thus precession frequency), this is more scalable, although the addressing problem still has no proposed solution [10].

Photonic A photonic quantum computer uses the direction of polarization of a photon as a qubit. Systems involve firing a light pulse through a set of lenses. This architecture has scalability problems; experiments seem to have topped out at about 11 qubits due to difficulties generating and reliably detecting many entangled photons. Recent reviews are [20, 21]. This architecture has important applications in provably-secure quantum communication and long-range coherent transport. Coupling of photons to other quantum-mechanical systems is a growing field (see §3). The original paper is [22]. Beautiful results have recently been demonstrated with optical memories at ANU [23] and similarly [24], temporarily storing photons coherently in excited states of a crystal.

P in Si: electron spin This architecture is similar to the Kane proposal but stores the spin on the phosphorus atom's valence electron instead of the nucleus [25, 26]. A P-31 atom replaces a silicon atom 20nm from the surface in a Si-28 crystal. All the Si-28 electrons are paired up, and Si-28 has no net nuclear spin so this is a very clean environment for the spin-1/2 P nucleus and its extra electron. The valence electron on the P atom is then controlled with metallic wires (GATES) on the surface of the crystal (Figure 1). One of the advantages of this architecture is that the gate fabrication process is highly mature thanks to the silicon chip industry, and 20nm gates are regularly produced in bulk.

Major hurdles for this architecture include manufacturability (positioning single phosphorus atoms is hard [27]) and transport [28]. Two competing methods for fabrication are ion implantation [27] and the bottom-up approach [29]. [30] is a recent review.

GaAs Quantum Dots Similar to the P in Si system, a quantum dot confines electrons using electrically charged gates instead of the potential well of a phosphorus atom. In gallium arsenide, the large sea of spins (~10^6 in interaction range) near the dot limits coherence times to a few microseconds. A quantum dot constructed in a no-nuclear-spin material may mitigate this problem [31, 32]. Coupled qubits in this architecture have been demonstrated [33] but the possibility of coherent transport remains an open question.

Ion trap In this architecture, ions (spin qubits) float in vacuum above a 2D network of electrical gates which control the ions [34]. This approach looks very promising in the short term. Ion traps transporting several qubits have been demonstrated by NIST Maryland [35], together with repeated gate operations [36]. Coherence times are measured in hours because there is very little for the ions to interact with. The current hurdle is heating of the ions by the trapping lasers or gates; this may be mitigated using magnetic gates [37]. This architecture is technologically expensive, requiring atomic cooling and high vacuum.

Superconductors SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES (SQUIDS) are small superconducting rings. For quantum computing, they store a qubit as the charge, phase of a current orbiting in the ring, or quantized magnetic flux through the ring. Coherence is more difficult in these systems because of additional energy levels above or below the two states used as qubit states [38]. A recent review is available [39].

Diamond The most popular diamond system uses the free electron in a nitrogen vacancy (NV) defect in a diamond crystal as the qubit. Coherence times of about 1 second at *room temperature* have been demonstrated in high-purity C-12 diamond in unpublished work. The best published result is 2ms [40]. Proposals use optical transport and readout, which can cause difficulty if qubits are close together due to difficulty focusing lasers to address individual NV centres. Manipulation is performed optically. For manufacture, NV centres can be located in smashed diamond crystal, shaped into 40nm "bricks" and assembled into larger structures or have diamond crystal grown around them. This system is promising, but novel manufacturing techniques are required, delaying progress [41]. NV centres can also be used on their own as sensitive localised magnetic field detectors [42]. Interaction is difficult, with schemes proposing using photons as mediators.

Other There are many other exotic architecture proposals. They include trapping an electron between a donor and the image charge of a donor in the nearby oxide [43], or using fullerenes [44, 13]. Many more are given in a more comprehensive review of current progress [10].

A more recent review focusing on solid-state systems is [40]. Figure 2 shows a summary of the coherence times for various solid-state systems.

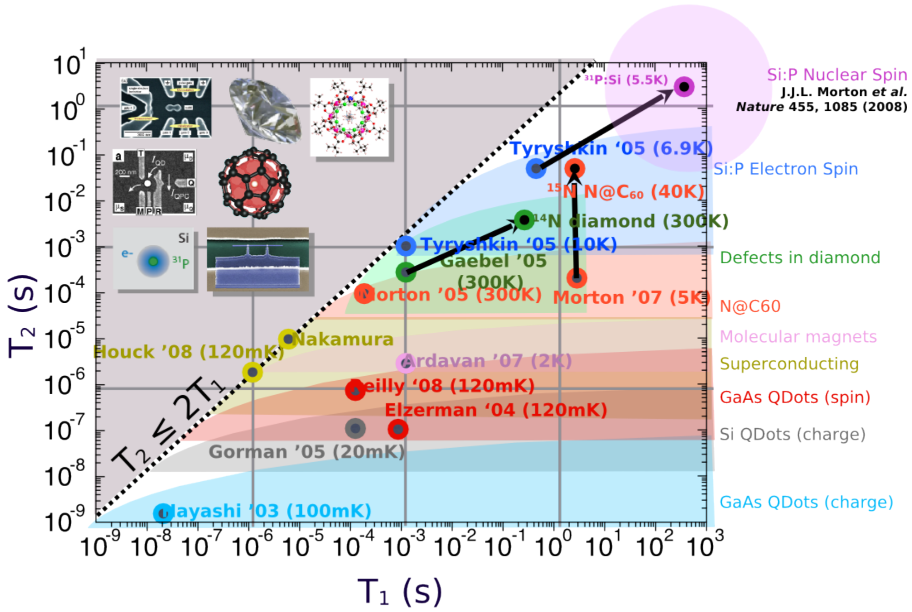


Figure 2: Coherence times of various solid-state systems. T_1 is the decay time for the system to relax into its ground state; T_2 is the time for two coherent states at different energy levels to build up a large phase difference so that they are effectively incoherent. Image by John Morton and Jessica van Donkelaar.

3 Coherent Transport

One of the necessary components of a quantum computer is the ability to transport qubits from one place to another. Several methods for qubit transport in electron-spin-based architectures have been proposed. Which method is the most technologically viable remains to be seen.

CTAP

COHERENT TRANSPORT BY ADIABATIC PASSAGE is a possibility for solid-state coherent transport [45]. In the simplest version of CTAP (Figure 3), there are three donors, two of which are ionised by gates. Barrier gates control the tunneling rate between adjacent donors. To move the electron from one end of the chain to the other, the barrier at the end of the chain is lowered and then raised. While

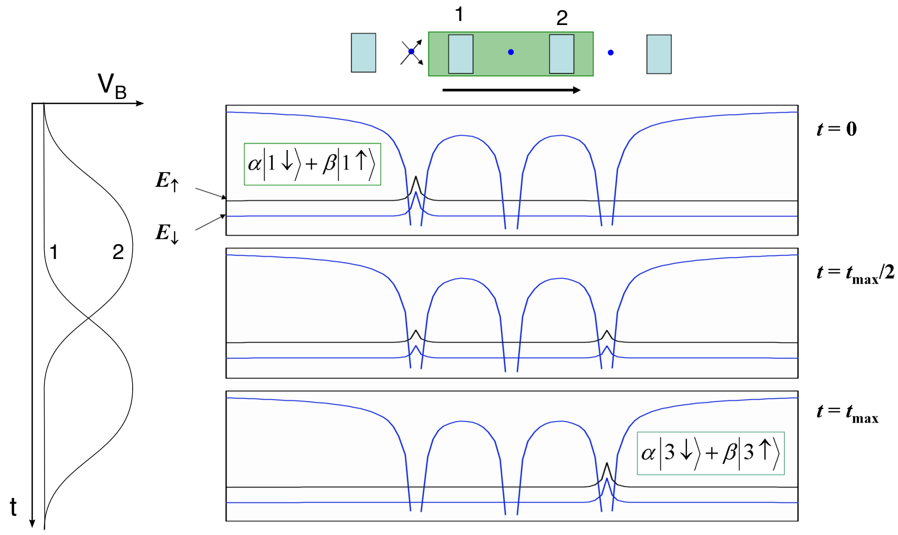


Figure 3: CTAP, from [45]. The left-hand graph shows the voltage applied to the barrier gates during the transport process. The right-hand graphs show the potential and energy levels at several points during the process. This non-intuitive process involves lowering the second barrier (by increasing the voltage on the second gate) before the first.

this barrier is being raised, the other barrier between the first two donors is lowered, and to complete the sequence the start barrier is raised. This counter-intuitive pulse sequence ideally results in no population of the electron on the intermediate atom at any point.

Using a simple electric field gradient to push the valence electron along a chain of ionised donors is also discussed in [45], and shown to have a lower fidelity. This may be a useful precursor study to perform, in particular to ensure that the electrons are available in a real device and can be moved around.

CTAP scalability is discussed in [46]. A recent study [47] using the NEMO 3D tight-binding simulation toolkit [48] shows that the scheme is extremely sensitive to the exact position of each donor. Tuning the protocol's gate voltages allows high fidelity transport for donor position variation of several lattice spacings or a few nanometres.

HETERONUCLEAR CTAP involves using a larger atom in the intermediate position. It may be easier to use a different atom for the central potential-well if that atom has a lower electron affinity and hence requires less accurate positioning [49].

Spin Bus

In its simplest form, a SPIN BUS [50, 51, 52] consists of an antiferromagnetic Ising-model chain of spins[3], tightly coupled to their neighbours but nothing else. At low enough temperatures, a bus with an odd number of sites N has two possible states: an extra spin-up or an extra spin-down. This allows treatment of the bus as an effective single spin.

To transfer spins, the bus is then coupled to the destination site, allowed to equilibriate, and then decoupled. It is then coupled to the source site, allowed to equilibriate and decoupled. This has the effect of transferring the spin at the source site to the destination site with high probability. This non-intuitive coupling order is reminiscent of CTAP.

Spin buses more than several hundred sites long (perhaps 1-10μm in solid state devices) are probably not practical due to long equilibrating times, donor diffusion and unintended coupling with parasitic sites. No spin bus has been demonstrated to date. A simple constraint on the temperature required for antiferromagnetic behaviour is derived in [53].

[3] i.e. spins prefer to antialign, up-down-up... or down-up-down...

A potentially more useful application of such a device is the generation of highly entangled states between many sites. This is because it is quite straightforward to couple many sites to the bus at once. An example is the procedure for generating a W_n state, $|00\ldots001\rangle + |00\ldots010\rangle + \cdots + |10\ldots000\rangle$, given in [52].

Photonic Coupling and The Flying Qubit

In the long term, it will be very important to be able to transport quantum information long distances. Divincenzo calls such transport FLYING QUBITS. Almost all proposed flying qubits use photons as the information carrier. Theoretical models of how to couple a quantum dot to a photon have been published [54], and preliminary work towards experimental demonstration has shown that quantum dots can absorb [55] and emit [56] single photons (in a directionally controlled way).

Optical coupling between single-electron quantum dots has been demonstrated [57]. Yamamoto's group has also demonstrated control over the quantum state of a single quantum dot using optical techniques [58]. Abanto's architecture [59] results in considerable leeway for solid state qubit donor placement by placing the donors in an optical cavity and coupling them using cavity modes instead of Coulomb interactions.

It is also possible to couple photons to excitons (electron-hole pairs) [60, 61]. The question of how to coherently couple such excitons to solid-state qubits remains open.

Projects to demonstrate long-range quantum entanglement have been successful between islands 144km apart [62] and are plans are afoot to do it via a satellite [63].

Blue Sky options

Coherent electron transport in carbon nanotubes has been demonstrated [64]. It may be possible to perform this kind of BALLISTIC TRANSPORT in the Si:P system. This would likely require atomically precise donor placement.

It has recently been shown that photosynthesis involves coherent transport [65]. Engel et. al. observed "remarkably long-lived" coherent states in FMO bacteriochlorophyll complexes at 77K. Perhaps if we understand this mechanism then we can do it on chip, maybe even by using actual chlorophyll molecules.

4 Si:P fabrication and measurement

In order to experimentally demonstrate some of the above coherent transport options, it is necessary to be able to accurately position donors. This section discusses techniques for doing so and potential experiments on fabricated structures.

Donor ion positioning

There are two main strategies for donor ion placement: "top-down" and "bottom-up". The bottom up process involves placing atoms on a silicon surface and then growing more silicon around them; top down involves implanting ions into a clean silicon lattice by ion implantation.

Ion implantation is less accurate; for 20nm depth, ions will straggle up/down and sideways an average of 8nm compared with about 1nm for bottom-up. The bottom-up approach currently involves a considerable effort to make a single device (and so is likely less scalable in the long term) and the epitaxially grown silicon lattice above the donors may be less crystalline.

Outlines of the bottom-up process are given in [66, 67]. The AFM step, involving removing a few hydrogen atoms from the surface of a silicon crystal, is discussed in [68]. A more accurate technique aiming for single-atom positioning using an STM tip is discussed in the letter [69] and the article [29]. This has recently resulted in the successful positioning of a single ion to within 1nm (3 lattice spacings).

The semiconductor industry has been using ion implantation to fabricate electronic devices since the 1950s. More recently, more accurate methods of implanting a counted number of ions have been demonstrated [70], down to exceptionally low energies of about 10keV [71]. The counting can be done by collecting secondary electrons emitted when the ion impacts the surface [72, 73], or by collecting the induced charge from the substrate after the impact [71]. It is quite difficult to focus a low-energy ion beam to below the micron range. Instead of relying on fine focus, the step and repeat system [74], a masking process relying on a mobile secondary mask [75], will allow 20nm resolution of donor placement.

Embedded nanowires

In two papers [76, 77], Iwano et. al. implant 100keV Ga into doped Si using a focused ion beam. The resulting wires are less than 100nm wide and about 50μm long, and were measured down to 4.2K. The conduction model is not fully explained in these papers. Iwano refers to it as the "Hopping model" but makes many assumptions without careful study. Most of the samples were annealed at 600-690°C and measurements show reduced conduction indicative of lattice defects.

Conductance measurements on 8nm wide monolayer-thick P in Si wires are performed in [78]. Rueß finds Ohmic conduction (1 in 4 atoms in the wire is a P atom) with the resistance heavily dependent on temperature. In the range 1-10 Kelvin, the resistance is also heavily dependent on the applied magnetic field (MAGNETORESISTANCE). They found several different conduction mechanisms were necessary to fit the measured data. Above 10K no magnetic field dependence was observed. At 4K, increased magnetic field increased the resistance (positive magnetoresistance), consistent with the 1D VARIABLE-RANGE-HOPPING (VRH) model [79]. This semi-classical model is based on conduction electrons tunneling between nearby phosphorus ions. It ignores non-localised effects of fully quantum-mechanical models such as Cooper pairing or ballistic transport. Positive magnetoresistance is consistent with the magnetic field perpendicular to the conduction plane squeezing the electron wave-function and hence reducing the tunneling rates and increasing resistance. At 1K, Rueß found a negative magnetorestance for small magnetic fields (0-1 Tesla), which is not well explained.

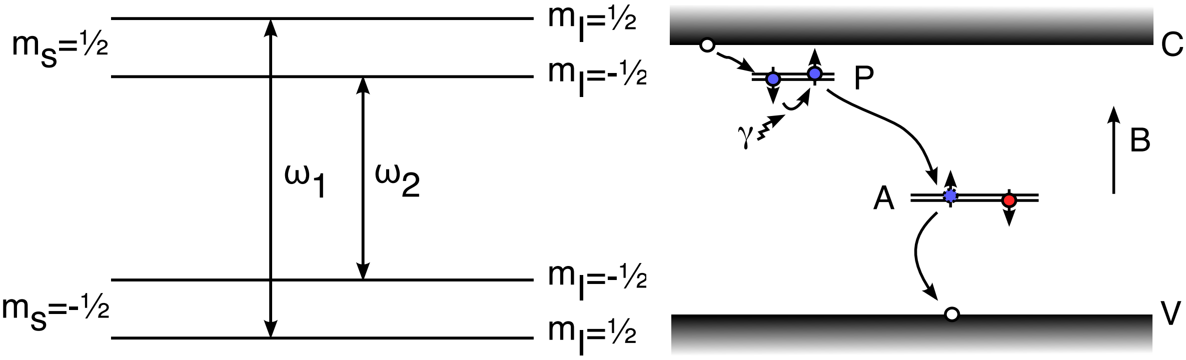
No conductance or EDMR studies of narrow implanted P:Si wires have been done.

Shin et. al. have made a SET so small (2nm channel) that it works at room temperature [80]. They claim to be able to do this reliably. This is a much easier method of fabricating quantum dots in silicon than positioning single ions. Coherence times for this system will probably be quite low because the oxide contains many noisy spins and is very close (1nm) to the electron.

ESR

The standard technique for detecting the species and electronic environment of certain donor atoms is through ESR. These techniques allow unambiguous identification of paramagnetic impurities by allowing measurement of their energy levels, which act much like a "fingerprint" for identifying donors. Such identification is important to be sure that the fabrication process has not resulted in other impurities such as crystal defects which will disrupt the electronic landscape of a quantum computer. These techniques will also allow us to ensure that the implanted donors are electrically active and that the phosphorus atom has an electron at home to be used as a qubit.

ESR (ELECTRON SPIN RESONANCE) is very similar to NMR [81]. A static magnetic field and a microwave-frequency EM field are applied to a sample. At a certain ratio of frequency to magnetic field, the sample will absorb more energy from the microwave field. An electron is in a bound state around an atom and in an applied magnetic field will have its energy levels split by the HYPERFINE SPLITTING or ZEEMAN EFFECT (Figure 4a), where a spin-down electron will have less energy than a spin-up electron due to alignment or anti-alignment with the magnetic field. The electron is allowed to transition between these states (flipping its spin), but only by absorbing or emitting a photon (or phonon) of the correct energy. If the material is allowed to relax in the magnetic field, there will tend to be considerably more electrons in the lower (GROUND) state than the upper excited state. The electron will thus tend to absorb photons of the correct energy from the applied microwave field, flipping it into its higher-energy state before it relaxes back down to its ground state via spontaneous emission of a phonon or photon (with a characteristic timescale of T_1). If the microwave field is of the wrong frequency, the ground-state electrons will not absorb as many photons. There is thus a certain



(a) (b)

Figure 4: (a) Hyperfine levels and the first-order transitions for a spin-$\frac{1}{2}$ nucleus (I) and electron (s), after [82]. (b) A band structure outline of the EDMR mechanism. A donor impurity such as a phosphorus atom (P) sits just below the conduction band. An recombination centre (A) sits between the donor and the valence band and provides a recombination pathway for the donor. However, if the P and A electron spins are aligned (not shown), the Pauli exclusion principle prevents the second electron from decaying from P to A and the recombination pathway is blocked.

set of frequencies at which the spins get flipped frequently, the sample is less magnetised and more photons get absorbed. These are the RESONANT FREQUENCIES, and from this we can work out the energy levels and thus identify the donor.

EDMR

EDMR (ELECTRICALLY DETECTED MAGNETIC RESONANCE) is a more sensitive method of detecting the ESR condition, and so can be used to detect a smaller number of donor atoms. To perform EDMR, a recombination centre is used to modifiy the number of charge carriers, depending on the ESR condition [83]. This results in a change in the conductance of the sample which can be directly measured.

An outline of the EDMR mechanism is shown in Figure 4b. To perform a pulsed EDMR experiment, the system is first initialised by placing it in a magnetic field. This orients the spins of the donor and recombination centre in the direction of the magnetic field (B). As we are interested in probing the P donor, we apply a microwave pulse (γ) at a phosphorus resonant frequency (ω_1 or ω_2 of Figure 4a) and observe that with more recombination, there will be fewer conduction electrons in the conduction band and a corresponding increase in the resistance, which can be directly measured.

EDMR has been demonstrated on a single electron from a quantum dot [84]. It has not yet been done on a single implanted phosphorus donor, although measurements of less than 100 donors [85] and theoretical analyses [86] of such a measurement have been published, relying on the P_b interface defect to act as the recombination centre.

The EDMR signal is normally enhanced using above-bandgap light to excite many carriers and hence make the recombination more pronounced [87]. This also suggests the technique of OPTICALLY-DETECTED MAGNETIC RESONANCE in which the luminescence of transitioning electrons is measured. Finally, spatially-resolved detection is possible by localising the optical carrier excitation [87] or conduction current with a scanning probe.

5 Conclusion

There are several methods for performing coherent transport in the solid state. It remains to be seen which transport mechanism can be physically implemented using state-of-the-art technology.

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